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FINAL REPORT

Investigation of a Substitute Fuel to Control Automotive Air Pollution

by

R. E. Fitch and J. D. Kilgroe

Prepared for

Division of Motor Vehicle Research and Development
National Air Pollution Control Administration

Contract CPA 22-69-70

Consolidated Engineering Technology Corporation
188 Whisman Road
Mountain View, California 94040

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FOREWORD

The work upon which this publication is based was performed pursuant to Contract No. CPA 22-69-70 with the Division of Motor Vehicle Research and Development, National Air Pollution Control Administration, CPE, Public Health Service, Department of Health, Education, and Welfare.

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1.0 INTRODUCTION

Air pollution by automotive exhaust emissions is a serious environmental problem which requires immediate solution. Substitute fuels for I. C. engines which show promise of significant reductions in emission pollution levels are being investigated under sponsorship of the National Air Pollution Control Administration (NAPCA). A substitute fuel which shows considerable promise is methanol (CH_3OH). Because of its physical and chemical properties it can be readily substituted for gasoline as an IC engine fuel with only minor engine modifications. Since it has no carbon-carbon bonds and already contains one oxygen atom the reaction kinetics for complete oxidization are theoretically less complex than those for gasoline and any intermediate reaction products are more readily eliminated in the exhaust system. The levels of unreacted or incompletely oxidized fuel could be further reduced or virtually eliminated by predecomposition or reforming the methanol into H_2 + CO prior to injection into the engine. This predecomposition into gaseous fuels would increase air and fuel mixing and provide gas phase reaction kinetics which would enhance combustion efficiency.

Disadvantages of methanol include its higher heat of vaporization and its lower heat of combustion (approximately 46 percent of gasoline) which results in higher fuel consumption. Although the estimated cost per gallon of large quantities of methanol is lower, the smaller heat of combustion would probably initially result in a net increase in the cost per mile. However, this cost could be partially or completely negated by performance gains accruing from use of engine waste heat for methanol decomposition into H_2 and CO prior to injection into the engine. Cost penalties for gasoline fueled engines resulting from increasingly more strict emission standards must also be accounted for.

The NAPCA funded program reported upon herein was conducted to investigate potential reductions of exhaust emission contamination levels which might result from the use of methanol in IC engines. The primary objectives were to investigate (1) the exhaust emissions and performance of an automobile modified for fuel operation on methanol and (2) the effects of methanol reforming or predecomposition upon laboratory engine emissions and performance.

2.0 SUMMARY

A study was conducted to investigate the feasibility of using methanol as a substitute fuel for gasoline to reduce exhaust pollutants emitted from automotive engines. Work was performed in two phases encompassing both automotive and single cylinder laboratory engine tests.

Phase I - Automotive Testing

Preliminary automotive tests were run to compare the exhaust emission levels of a current automobile IC engine using gasoline and methanol fuels. A used 1969 Dodge Dart with a 225 cu. in. slant six engine was utilized for the automotive engine tests. The engine was tuned to factory specifications and the car was submitted to five standard (seven mode cycle) cold start exhaust emission tests at the State of California Air Resources Laboratory (ARL) to obtain comparative gasoline emission data. The engine was subsequently set-up to run on methanol by the installation of a Zenith carburetor modified for higher fuel flow rates, a heat exchanger block to increase carburetor and intake manifold heating, and an electric fuel pump.

Emission testing with the methanol fueled engine was conducted at the ARL test facilities in Los Angeles and the Chevron Research laboratories in Richmond, California. The ARL tests consisted of four standard California cold start seven mode cycle tests and several special steady state emission tests. The Chevron tests included standard Federal cold start seven mode cycle tests, steady state cruise emission tests, cylinder distribution tests and air-to-fuel ratio tests.

Instrumentation included non-dispersive infrared (NDIR), flame ionization detector (FID) and gas chromatograph (GC) analyzers. The ARL tests were conducted for several carburetor configurations using

standard California gasoline engine sampling techniques. Two carburetion configurations were tested in the Chevron tests. Exhaust samples were collected using a Scott variable dilution sampler and a heated sample bag to prevent loss of unburned methanol and aldehydes by water condensate absorption. Special tests were also run to calibrate the NDIR and FID analyzers for methanol emission concentrations.

The ARL data indicated large concentrations of CO and hydrocarbons in the exhaust (methanol reported as hydrocarbons). The hydrocarbon data indicated a constant build-up during the successive test cycles and are questionable because of the sampling techniques used. The NO_x emissions were considerably reduced from those measured during the gasoline fueled tests.

The Chevron test data indicated that the engine was running fuel rich for the two carburetor jet configurations used in the tests. Cylinder exhaust data indicated a considerable deviation in exhaust emissions between cylinders. Total unburned hydrocarbon emissions excluding methanol were low, being 40 and 19 PPM (hexane equivalents) respectively for the two carburetor configurations. Methanol emissions ranged from approximately 4300 to 1900 PPM (methanol) for the cold start seven mode cycle tests. Extrapolation of the data to leaner a/f ratios indicates that methanol emissions well below these levels can be realized. NO_x emissions for the less rich carburetor configuration were 1050 PPM as compared to an average of 1463 PPM for the gasoline tests. Formaldehyde emissions were 110 PPM (formaldehyde) for the least rich carburetor condition.

With the exception of cold start problems and a slight decrease in performance using methanol, the drivability of the methanol and gasoline fueled car was comparable.

Phase II - Laboratory Reform Gas Testing

Laboratory emission tests were conducted using a single cylinder CFR variable compression ratio research engine. The effects of compression ratio, fuel to air ratio, percentage of methanol dissociation, intake manifold mixture temperature, and timing on engine performance and exhaust emissions were investigated. Methanol, formaldehyde, CO, CO_2, and O_2 emissions were measured. Methanol dissociation was simulated by use of pre-mixed H_2 and CO gases.

A 30% dissociation in methanol resulted in a 65% reduction in unburned methanol and a 48% reduction in formaldehyde emissions when compared with pure methanol at similar mixture and compression ratios. At 50% methanol dissociation, unburned methanol and formaldehyde emission levels were reduced 81% and 71% respectively. At 100% dissociation, the methanol and formaldehyde exhaust concentrations were reduced to non-detectable levels. At a compression ratio of 15:1 and 70% methanol dissociation a maximum decrease in brake specific fuel consumption of approximately 7.4% was achieved. Emissions were reduced by intake manifold mixture heating and by operation at high air-to-fuel ratios.

Conclusions

It is concluded that methanol displays significant potential as a pollution control substitute fuel for gasoline. In the automotive tests conducted with a slightly modified, non-optimized engine system, methanol was shown to be a satisfactory fuel from the standpoint of engine operation and to produce methanol emissions as low as 1900 PPM (317 PPM-hexane equivalent). Vehicle mileage was low (7 to 9 mpg) as expected. Suspected high aldehyde emissions were confirmed. It is, however, believed that optimization of the fuel-air ratio, the mixture distribution to the cylinders, and heating of the fuel or fuel-air mixture, will result in improved performance and

substantially reduced emissions of all pollutants, except NO_x.

Laboratory engine operation with blends of reform gases ($CO + 2H_2$) and methanol was shown to be successful in improving engine performance (subject to engine knock limitations) and providing major reductions in methanol and formaldehyde emissions. If the reforming technique can be economically implemented in an automotive system, it is highly probable that emission levels can be achieved which are well below those possible with gasoline.

3.0 TECHNICAL ACTIVITIES

The program encompassed two major work tasks which included automotive engine emission tests, and laboratory engine emission tests.

3.1 Automotive Engine Tests

Automotive engine tests of a car fueled first on gasoline and then methanol were conducted to obtain comparative exhaust emission and vehicle drivability data.

3.1.1 Gasoline Fueled Engine Exhaust Emission Tests

Test Equipment and Procedures

A 1969 Dodge Dart with a 225 cu. in. slant six engine and an automatic transmission was selected for the comparative gasoline and methanol tests. The Chrysler Corporation 225 cu. in. engine was selected because of the availability of other performance and exhaust emission data and the relative simplicity of the carburetor modifications required for methanol operation. Significant engine specifications are presented in Table I.

A car with 13,000 accumulated miles was leased for use on the program. Prior to emission testing the vehicle was given a "factory authorized" major motor tune-up, the wheels were balanced, the front end was aligned and the oil and filter were changed.

After the vehicle tune-up the car was driven to Los Angeles for engine emission tests at the State of California Air Resources Laboratory (ARL). A total of six cold start vehicle and engine exhaust emission tests were performed in accordance with standards defined by the State of California Air Resources Board.[1]* Due to an instrumentation problem, data was obtained from only five of these tests.

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* Superscript numbers denote references listed on page 31.

Each test was performed early in the day after an overnight cold soak. Both continuous NDIR and bag data were recorded.

Before each overnight cold soak the car was driven three times around the State of California's Air Resources Board test route Number 2 to accumulate typical metropolitan mileage between tests. Table II shows an approximate break-down of the type of driving represented by the route. Average speed over the route was approximately 16 to 18 miles per hour depending upon traffic conditions.

Following completion of the ARL tests the test car was towed back to the CETEC facilities in Mountain View where the engine head was removed and the engine pistons, valves and cylinders were inspected. The engine was then reassembled, the oil was changed and modifications of the engine for methanol usage were begun.

Test Results and Analysis

A summary of the average NDIR and gas chromatograph (bag) data from the five successful cold start tests is presented in Table III. Average data from the last two hot seven mode cycles (cycles 6 and 7) for each test is shown in Figure 1 along with the 1968 State of California standard and surveillance data for 1968 Chrysler Corporation vehicles.[2]

The HC emissions agree fairly well with the California Standard and 1968 Chrysler vehicle emission data while the CO emission data appear to be approximately 0.5% higher. The NO_x data are fairly consistent except for the results of test 3 which were abnormally high. Taken as a whole the emission data were higher than expected, but not unreasonable.

An inspection of the pistons, cylinders, valves and head conducted after the completion of the emission tests revealed some grey deposit, around the top of the cylinder walls, on the cylinder head and on the face of the head near the intake valves.

3.1.2 Engine Modifications for Methanol

Modifications were made on the Dart slant six engine to allow the test vehicle to be operated on methanol. Principle modifications included installation of a new carburetor, an intake manifold, a heat exchanger between the intake manifold and carburetor, an electric fuel pump and a new air cleaner assembly.

A Zenith 32NDIX carburetor, a stock European carburetor normally used on Mercedes Benz and Porsche engines, was selected for use because of its flexibility and availability. The Zenith 32NDIX is a dual barrel carburetor with replaceable air and fuel metering elements. A drawing showing various components of the carburetor is presented in Figure 2. To mate the carburetor with the slant six engine, a stock intake manifold was reworked by milling down the existing single barrel intake flange casting and by brazing on a dual throat adapter plate. Throttle linkage adjustments were made as required and a manual choke was added.

The initial engine runs were made with main and idling jet areas increased by about 20 percent and with the original carburetor venturi barrels. For these conditions the engine could be started but idled roughly, had virtually no acceleration and would operate under load only at very low throttle settings. Although the carburetion was evidently lean the engine was also running very cold as evidenced by condensation of water vapor on the outside surface of the intake manifold. In an attempt to improve engine operation, a heat exchanger element, through which hot water from the engine heater hoses was circulated, was installed in the air cleaner. This did not provide adequate heating. Subsequently a hot water heat exchanger was fabricated from 1/2 inch aluminum plate and was installed between the base of the carburetor and the intake manifold. With this modification both the carburetor and intake manifold ran warmer and the engine operation was much smoother.

To obtain satisfactory engine performance over the entire throttle range it was necessary to change the size of the carburetor venturi throats, idling jets, idling air jets, main jets and pump or accelerator jets. Engine performance tests were made with various fuel and air metering orifice sizes. Primary venturi sizes (diameters) tested were 0.985, 0.840 and 0.760 inches. The idle jet, pump jet and pump discharge tube diameters were held constant at 0.030, 0.025, and 0.025 inches respectively. Main jet diameters of 0.045, 0.055, 0.060, 0.064, 0.070 and 0.073 inches and air correction jet diameters of 0.062 and 0.109 inches were tested. The 0.760 diameter venturi in combination with the 0.064, 0.070 and 0.073 inch diameter main jets provided the best overall driving operation with increased performance with increasing jet diameter. Since the 0.064 inch diameter jets gave satisfactory engine performance and probably the lowest emission levels because of its relative leanness they were selected for the ARL emission tests. An engine exhaust emission analysis of CO, O_2 and CO_2 in this carburetor configuration, with the motor running at 45 mph and a 15 ft-lb dynamometer reading, indicated that the engine was operating at an air to fuel ratio of 7.4. The car performance with these elements came close to matching performance of the car when it was operating on gasoline.

The carburetor heating sometimes resulted in methanol boil-over after the engine was turned off. A by-pass line with a 0.04 orifice was installed in the fuel line between the downstream side of the fuel filter and the upstream side of the fuel pump to allow fuel from the float bowl to drain back into the fuel tank after the engine was stopped. This appeared to solve the boil-over problem, but made the engine harder to start and often resulted in stalling of the engine several times during start-up. This latter problem was solved by installing an electrical fuel pump in the by-pass line in parallel with the original fuel pump.

3.1.3 Methanol Emissions Testing

Emission Measurement and Reporting

A brief discussion of the methods and units which have been used to measure and describe the hydrocarbon and methanol emission data which appear in this report is necessary in order to establish a proper basis for comparison. With the exception of some data of Chevron Research, the methanol and hydrocarbon exhaust concentrations have been reported as parts per million (by volume). It is important to note that hydrocarbons, as used herein, refer to non-oxygenated true hydrocarbons except in the ARL tests. Methanol is reported separately as methanol. Except as noted elsewhere, the following table indicates units and equivalents used to describe the exhaust concentrations measured by ARL and Chevron Research in the auto testing, and by CETEC in the CFR engine testing.

	Hydrocarbon	Methanol	Formaldehyde
ARL	PPM Hexane Equiv.	PPM Hexane Equiv.	Tot. Aldehydes as Form. (MBTH)
Chevron	PPM Hexane Equiv.	PPM Methanol	PPM Formaldehyde
CETEC	not measured	PPM Methanol	PPM Formaldehyde

It should further be noted that the carbon equivalent of methanol is one-sixth that of hexane. When reviewing the data presented herein, it is important to keep in mind that one thousand parts per million of methanol is 1000 PPM when reported as methanol, but is 167 PPM when reported in terms of the hexane standard on the basis of carbon equivalence.

Testing Equipment and Procedures

Emission tests were run on the modified test vehicle at the California ARL facility and the Chevron Research facilities in Richmond,

California. The ARL tests consisted of four standard cold start tests run for three different carburetion configurations. A venturi diameter of 0.76 inches was used for all tests. Main jet diameters of .064, 0.070 and 0.073 inches were used. Except for three additional hot cycles and a special hot cycle purge on Test 8 the tests were performed in accordance with Reference 1. Data was acquired from both NDIR and FID instrumentation.

After the sixth ARL test (first methanol test) the car was driven three times around the LA-2 driving route before being returned to the test facility for the overnight cold soak. After the seventh test the car was driven approximately 20 miles to the L. A. International airport to obtain some new carburetor elements. The main jets and air correction jets were changed at the airport and the test vehicle was driven back to the ARL test facility for overnight cold soak. The main jets were again changed immediately after cold start emission Test Number eight and the car was driven three times around the LA-2 route prior to the overnight cold soak storage. After the ninth and final ARL emission test the car was driven back to the CETEC Mountain View facilities where the engine was again dismantled and inspected.

Further emissions testing on the methanol car were conducted at the Chevron Research facilities in Richmond, California. Emission tests were run using the Federal seven mode cycle[3] which is essentially identical to standard State of California cold start test. Drivability tests, 40 mph steady state cruise tests, cylinder emission distribution tests, and air-to-fuel ratio tests were also run. Emission analyses were conducted using basic NDIR, FID, and gas chromatograph (FID) techniques. The major difference between the State of California Air Resources Laboratory (ARL) tests and the Chevron tests were the emissions sampling methods used. In the Chevron tests the samples were diluted with a Scott variable dilution sampler to ratios of 6.5 to 7.0 to prevent build-up of methanol and aldehydes in the sampling

apparatus. Also the emissions reported as HC at ARL were further broken down by Chevron into unburned HC and unburned methanol by FID analysis of the total HC plus methanol concentration. This was accomplished by reanalysis of the HC content after filtering recycled emissions through a dry ice trap to condense out any methanol and aldehydes.

Tests for two carburetor configurations were conducted. The first carburetor configuration tested contained 0.070 main jets and air correction jets of 0.053. The second had 0.063 main jets and 0.060 air correction jets.

Test Results and Analyses - ARL

Analysis of the ARL test data indicated that the unburned hydrocarbon and methanol emissions were quite high relative to controlled gasoline engine emissions.[4] These high levels resulted from fuel rich carburetion and, as determined from the Chevron tests, poor intake manifold distribution (either a/f or temperature). A summary of the average continuous NDIR and bag emission data obtained from the four ARL tests is presented in Table IV. Fuel rich carburetion for each of the tests is indicated by the relatively high concentrations of carbon monoxide and hydrocarbons. If it is assumed that there is negligible O_2 in the exhaust, which seem likely from the high CO levels, then the air to fuel ratios for the hot cycle tests, calculated from the exhaust composition, vary from 5.2:1 to 6.2:1 (see Table V). A break down of hydrocarbon emission data obtained by GC analysis of Test Number Six bag samples indicates that the HC emissions (both pure and oxygenated) are more than half methanol (see Table VI). Both the continuous sample and bag data shown in Table IV are believed to present lower average concentrations than are actually present in the exhaust emissions. This evidently was caused by absorption of methanol and aldehyde emissions in the sample traps used to cool and

condense water vapor from the exhaust. This conclusion is supported by the continuous NDIR data which indicates an increasing build-up of measured hydrocarbons in each of the first four successive cycles as the traps become saturated and absorb less methanol. This is illustrated by the continuous sample hydrocarbon data for the first four cycles of Test Number Six as shown in Figure 3. In the fifth cycle no data is collected and the sampling system is purged. The HC emissions on the sixth cycle were decreased nearly to the level measured on the second cycle, while the seventh cycle emissions showed the typical increase.

After completion of the ARL emission tests the car was driven back to the CETEC facilities in Mountain View where the engine was inspected. Much of the deposits on the head around the valves noted after the gasoline tests were gone as well as most of the deposits on the face of the pistons. Some surface oxidation (rust) of the cylinder heads and piston faces was noted. No rust was found on the cylinder walls.

Test Results and Analyses - Chevron Research

Testing of the Dodge was conducted by Chevron Research in Richmond, California to obtain additional emission and drivability data[5]. Tests for two carburetor configurations were run, the first with 0.070 main jets and air correction jets of 0.053; the second had 0.063 main jets and 0.060 air correction jets. Engine operation with the 0.070 main jets was very fuel rich. The 0.063 main jets provided leaner operation but resulted in a fuel rich average seven mode cycle. Data on the air-to-fuel mixture ratios as a function of speed for the two carburetor configurations is presented in Figure 4. The emission data show large quantities of unburned methanol and formaldehyde in the exhaust (see Table VII). The data from the leaner of the two carburetion configurations indicated a significant improvement over the more fuel rich conditions.

In addition to the rich carburetion conditions, measurements at the exhaust manifold near cylinders 1, 2, and 3 indicated a wide variation between cylinders (see Table VIII).

While in general the methanol emission levels were relatively high, these problems can be attributed primarily to the fuel rich carburetion and apparent poor combustion efficiencies. As indicated by Table VII the unburned methanol and hydrocarbon emissions were more than halved by use of the leaner 0.063 main jets. Because the cold start cycle is run predominately over the speed ranges which were fuel rich for both the 0.070 and 0.063 main jets, a considerably larger reduction of the unburned methanol emission levels could be expected if the carburetion were changed to provide a lean mixture ratio over the entire speed range. The drivability at the less rich condition is discussed in a later paragraph. It is possible that completely lean operation may result in a loss of drivability, but this could possibly be off-set by optimization of the intake heating.

Data presented in Table VIII show a large difference in exhaust CO and NO_x concentrations between cylinders 1, 2, and 3. The most probable cause for these large differences in emission level concentrations is believed to be changes in combustion efficiency resulting from variation in intake mixture temperature. This postulate is given credence by the laboratory tests discussed in section 3.2.3.1, which indicated that inlet temperature has a significant effect on emission and performance levels and hence, by inference, upon combustion efficiencies. The mixture temperature in the intake manifold of cylinder 6, at 50 mph steady-state conditions, was measured and found to be 4°F. This strongly suggests that considerable liquid fuel was being injected into the cylinder - not a satisfactory condition from the standpoint of emissions.

Figure 5 presents emission data from the cold start seven mode cycle in Table VII as a function of average intake air-to-fuel ratio estimated from Figure 4. It is important to note that the HC emissions are less than 50 ppm for even the very fuel rich carburetion and drop to less than 20 ppm for the fuel rich 0.063 main jet configuration. The unburned methanol and CO data indicate that, by extrapolation to leaner mixture ratios, considerable reduction in these pollutants can be expected. Considering that the lower value of 1900 PPM methanol for the less rich condition would be 317 PPM if reported as hexane equivalents (as is common for hydrocarbon fuels), it does not seem at all unreasonable to project minimum values below the average level of 341 PPM (Hexane Equivalents) reported by ARL for the gasoline testing (Table III). Of course, these data alone are insufficient to enable prediction of the minimum levels which would be possible with this non-optimized system.

Chevron Research measured the total aldehydes over the 7 mode cycle for both carburetor conditions. However, because of uncertainties in the analyses, they feel that their earlier reported levels may have been high and have chosen not to report them as valid data. Consequently, the aldehyde emissions of the Dodge as functions of a/f are unknown.

The NO_x levels measured by Chevron (1050 ppm) were roughly comparable to the average Bag NO_x data on the ARL tests (978 ppm) and were about 1/3 of those reported for the gasoline tests. These levels should increase with increased combustion efficiencies and chemically correct mixture ratios which would be obtained with more optimum carburetion. However, the NO_x emissions from methanol combustion should remain below those obtained from gasoline because of the lower methanol combustion temperature.[6]

The drivability of the methanol fueled car was in most aspects comparable to the car fueled on gasoline. The biggest problem was cold

start of the engine which seemed to get progressively worse with decreasing cold start temperatures. At temperatures around 70° cold starting of the engine was similar to that with the gasoline fueled engine. At temperatures from about 50 to 60°F the engine was somewhat temperamental and sometimes required pumping and several restarts.

In cold start tests performed at Chevron for two different carburetor settings at 40°F, the car was extremely hard to start and required extensive pumping of the throttle and a number of restarts. With the initial rich carburetor configuration run, the alcohol fired back through the carburetor several times and required a boost from a battery charger before finally starting. The engine required four restarts on the first run and two restarts on the second leaner carburetion configuration run. The cold engine performance was marginally better on the second leaner run, but there appeared to be a noticeable lack of pep. The most significant improvement in the performance during the second run was a noticeably smoother idle. These cold start problems suggest that some method of providing manifold heat is needed to improve cold startability at low ambient temperatures. Fully warm performance was highly improved with the second (leaner) run, also. Not only was idle smoother, but there was less indication of stumble and surge during the constant manifold pressure accelerations.

In the Chevron tests, acceleration times were measured for accelerations from 30 mph to 60 mph in high gear. Average time for the first set (most rich) was 12.8 seconds, while the average time for the second set (less rich) was 14.5 seconds - an almost 2-second increase in average acceleration time for the leaner condition.

3.2 Laboratory Engine Tests

Engine tests were conducted at the University of Santa Clara M. E. Laboratory. The purpose of these tests was to investigate the effects of methanol predecomposition, a/f, compression ratio, intake manifold temperature and timing on emissions and performance.

3.2.1 Description of Test Apparatus

The primary laboratory test tool consisted of a Cooperative Fuel Research (CFR) variable compression ratio engine[7] and apparatus to measure and vary operating conditions. These included an input air flow meter, a cradle dynamometer, a knockmeter, tachometer and thermocouples. Auxiliary equipment consisted of (1) a liquid and gaseous flow metering system, (2) emission measurement apparatus and (3) sampling and recording devices. Figure 6 shows the arrangement of the test apparatus.

Flow Metering

Intake air flow was measured by determining the pressure drop across a calibrated orifice flowing into a plenum fabricated from two 55 gallon steel drums welded together. Plenum chamber pressure oscillations resulting from cycling of the single cylinder engine were minimized by a rubber diaphram mounted in the chamber head. The chamber outlet was connected to the CFR engine carburetor intake by a 4 inch flexible hose.

Instantaneous liquid and gaseous fuel flow rates were measured by use of a variable area flow-meter. Fuel flow was varied with a throttling valve downstream of the flow-meter and by regulator adjustment of the flow-meter inlet pressure. Pre-mixed gaseous fuel ($2H_2+CO$) was supplied from two high pressure cylinders manifolded to a single pressure regulator mounted in series with a variable area flow-meter and throttling valve. The gaseous fuel was injected into a mixing manifold just upstream of the CFR engine carburetor inlet. Liquid fuel was gravity-fed from the metering system into the fed line between engine

float bowl and fuel level indicators. The liquid metering system also consisted of a variable area flow-meter in series with a flow throttling valve. Liquid methanol flow rate during any test run was also determined by using a Toledo scale and stop watch.

Instrumentation

Instrumentation included equipment for measuring engine loads, engine speed, fuel and air consumption, engine temperatures, and exhaust emissions.

Engine loads were measured on the dynamometer balance scale. Approximate engine speeds for adjustment of engine run conditions was obtained from the electrical dynamometer tachometer. Engine speed for data purposes was acquired from a mechanical tachometer engaged with the dynamometer drive shaft.

Engine temperatures were measured by thermocouples and were recorded on two strip charts. The engine exhaust temperature was recorded continuously on a Daystrom-Weston 5701 recorder. The remaining measurements were recorded on a Daystrom-Weston 6702 multipoint recorder with a sampling rate of approximately once every minute. Table IX lists the temperature data recorded for each test.

CO, CO_2 and O_2 exhaust concentrations were obtained by Orsat analysis. On some tests CO_2 and O_2 data were also obtained by Beckman NDIR-2 analyzers to verify the accuracy of the Orsat readings.

Aliquots of aqueous scrubber solution samples were obtained by bubbling a measured volume of the exhaust through a fritted glass bubbler immersed in water. Methanol concentrations were determined by gas chromatograph with a flame ionization detector. Formaldehyde concentrations were determined by analysis of the aqueous scrubber solution using Denige's method for "Detection and Estimation of Small Quantities of Formaldehyde".[8]

3.2.2 Test Plan and Procedures

The methanol CFR laboratory engine tests were structured to investigate the effects of engine parameters upon performance and exhaust emissions. Basic engine parameters varied included compression ratio, air-to-fuel ratio, percent of liquid fuel dissociation, fuel-air mixture, engine inlet temperature, and spark timing. Table X presents a listing of the planned CFR engine test matrix. This matrix shows the nominal variables used and the major objective for each block of tests. Tests were run at four different compression ratios varying from a low of 8.4:1, corresponding to the compression ratio on the slant six, 225 cu. in. Dart engine, to a high of 15:1. Nominal air-to-fuel ratios included: one fuel rich mixture ratio (5.5), the stoichiometric mixture ratio (6.5) and two lean mixture ratios (7.5 and 9.0). To investigate the reforming concept nominal simulated liquid fuel dissociation percentages of 0, 30, 70 and 100 were tested. Since preheating of the intake air-fuel mixture with waste heat provided smoother engine operation with the automobile, tests were conducted with both heated and unheated air-fuel mixtures. In the initial tests the engine timing was varied to give optimum engine operation for the engine test conditions during each run; however, it became apparent that the timing produced a second order effect on engine power output. The timing was subsequently held constant at 10° BTDC.

Engine performance data and air-to-fuel ratios, both intake and exhaust, were measured on all tests. Emission data included exhaust CO, CO_2 and O_2 for all tests, and formaldehyde and methanol emissions on approximately 70% of the tests. Additional emission analyses were not possible because of the limited scope of the program.

After initial engine warm-up with liquid methanol and setting of the desired engine compression ratio the fuel flow rate was adjusted by use of the flow metering liquid and/or gaseous fuel throttling valves, until an air-to-fuel mixture ratio approximating the planned nominal value was achieved.

To obtain the nominal air-to-fuel ratio the engine load was varied and the engine speed was held between approximately 800 and 900 RPM.

Formaldehyde and methanol emission samples were collected for analysis by bubbling a measured exhaust sample through a fritted glass bubbler immersed in 200 ml of water. These gaseous exhaust samples were drawn from the exhaust by a vacuum pump, first through the bubbler and then a wet test displacement flow meter. Care was taken to place the bubbler as close to the exhaust pipe (a few inches) as possible, in order to avoid condensation and loss of the methanol and aldehydes. The total volume of exhaust gases drawn through the water scrubber was increased for tests with 100 percent dissociation in an attempt to obtain aqueous solutions with concentrations high enough to be analyzed.

The O_2, CO_2 and CO exhaust samples were also collected after passing the sample gases through a water scrubber

The variable area liquid and gas flow meters were calibrated by use of wet test positive displacement meters.

Ice bath reference junctions were used for the thermocouple temperature measurements.

3.2.3 Results and Data Evaluation

The results of the laboratory testing show striking trends in the influence of the major operating parameters on some of the emission and performance variables. The tests with pure methanol confirm those dominant characteristics of combustion behavior and performance which were observed with the auto, e.g., sensitivity of performance to intake temperature, critical effect of air/fuel ratio, etc. Furthermore, the effect on emissions of the blends of methanol and reformer gas was even more dramatic and pronounced than was expected. However,

there were no major surprises encountered, or basic differences between expected and observed behavior for either the liquid or blended fuels. The improvement in engine brake performance with the gas blends was less than was hoped for, but this somewhat negative result must, with the limited testing, be attributed to improper setup of engine conditions (timing, intake temperature, etc.) or other operational uncertainty.

The following subsections present first the emission test data as functions of the major test variables of a/f, C.R., and degree of fuel dissociation, followed by the engine performance results. Tabulated engine test data are given in the Appendix.

3.2.3.1 Exhaust Emissions

The exhaust constituents which were measured were methanol, formaldehyde, CO_2, CO, and O_2. The methanol and formaldehyde were collected in aqueous solutions and analyzed by gas chromatograph (FID) and wet chemistry, respectively. These analyses are fairly precise. The CO_2, O_2 and CO were measured with the Orsat apparatus and hence the data are subject to more scatter.

CO_2, CO, and O_2

Figure 7 is a composite graph of the data for all runs, plotted versus the intake-measured a/f ($\dot{w}_a/\dot{w}_f$). Individual plots as functions of the major operating parameters do not reveal specific trends with respect to those parameters owing to the scatter or lack of precision. Figure 7 appears to be typical of IC engines, except that the curves are slightly displaced. The point of best combustion appears to occur at a measured a/f of 6.1, although the chemically correct or stoichiometric a/f is 6.49 for methanol. This indicates that the measured a/f is low. As the fuel flow was carefully measured on a precision weight scale, it appears that the measured air flow rate

is in error on the low side. This seems to be confirmed by the data in Figure 8. Here the ratio between a/f calculated from the exhaust composition and the measured intake a/f is plotted against RPM. These data show that the intake a/f is consistently several percent lower than the exhaust, except near 820 RPM, where it appears that resonance of the diaphragm on the top of the orifice tank causes the average manometer Δh to read high. This resonance problem has been encountered before with this apparatus.

Methanol and Formaldehyde

Figures 9 through 12 show the exhaust concentrations of methanol and formaldehyde versus intake a/f as functions of the fuel dissociation level. The general shape of the overall curve is shown in Figure 9 for a CR of 8.4 and no dissociation. Both formaldehyde and methanol are strongly a function of a/f, with the formaldehyde minimum occurring at a slightly rich a/f and the methanol minimum slightly lean. Although the total test matrix is incomplete, it appears that this trend holds true for CR of 11, 13 and 15 and dissociation levels approaching 100%.

It is important to note that the methanol and formaldehyde emission levels with the liquid fuel at the 8.4 CR are comparable to those reported by Chevron Research for the Dodge. At a/f from 3.5 to 4.5 the levels range between 3600 to 2000 PPM for methanol and 60-100 PPM for formaldehyde, respectively. This strongly indicates that the trends shown on these figures are typical of what could be expected of the automotive engines if the carburetion, manifolding and intake temperature were tailored for best emission performance.

Without taking great liberties with the data described above, it is possible to show, even with the scatter which exists, the effects of CR, as in Figure 13. This crossplot of emission vs CR at a constant intake a/f of 6.5 shows a clear trend, at all dissociation levels

except 100%, towards minimum emissions at the low CR. However, they appear to be a maximum at a CR of approximately 13. This suggests that even higher ratios than 15 may produce significantly lower emissions, although a power limit may be imposed by knocking as discussed later.

The most satisfying and important trend is clearly shown in Figure 14 in which emissions are plotted versus percent dissociation (nominal value). This indicates that significant reductions in emission levels can be obtained from partial dissociation or reforming. At a CR of 11, 30% dissociation reduces methanol emissions by 65% from 500 to 280 ppm, and 50% dissociation reduces emissions to 19% or 150 ppm. The reduction in formaldehyde levels is also generally progressive but to a lesser degree than methanol.

Mr. Roy Lee, Phillips Petroleum of Bartlesville, Oklahoma, has advised, in private communication, that in the testing which he performed in the summer of 1968, he achieved the same results with pure reformed gases ($CO + 2H_2$): nondetectible emissions of methanol, aldehydes, and hydrocarbons. He reported no operational problems with the gases except for a tendency of the hydrogen to preignite at the combustion chamber surface.

These tests conducted by CETEC and Phillips Petroleum Co. confirm that reformed methanol is an exceptionally clean burning fuel, as was predicted, and that little or no tendency exists for recombination to higher molecules, especially at a/f near to or greater than stoichiometric.

Another striking result of these tests, as shown in Figure 15, is the confirmation of the critical importance of intake manifold heating. At an a/f of 6.5, the methanol and formaldehyde emissions decreased by factors of 3 and 2, respectively, when the intake mixture temperature was increased from 48°F to 71°F.

The virtue of the reformer concept as a means to reduce or eliminate hydrocarbon (including methanol) and aldehyde emissions has been abundantly demonstrated. However, its faults and techniques for practical implementation remain to be examined.

3.2.3.2 Engine Performance

The engine performance data, while indicating qualitative trends, does not show the striking effects just described for the emissions. This is due, in part, to the difficulty in maintaining and measuring precise load and RPM conditions. Also, little effort was made to adjust, for maximum performance, the other operating variables which are significant (spark timing, manifold pressure, manifold temperature, etc.). Furthermore, all tests were conducted at wide-open-throttle conditions, there being no throttle control on the standard knock measuring carburetor. It is believed, therefore, that the performance results are not entirely representative of the best that could be expected from the engine, were the tests conducted with engine performance and not emissions as the critical consideration.

Engine Power

Figures 16 and 17 show engine brake power for all runs plotted against intake a/f, for lines of constant dissociation level (moninal value). Power varies in the expected manner: (1) maximizes at a rich a/f, decreases strongly as a/f increases, (2) increases with compression ratio, (3) is greater for cold intake due to larger charge and less compression work and (4) decreases with increasing dissociation due to smaller mass charge and greater relative compression work. The effects of CR and degree of dissociation are shown independently in Figure 18 for a constant a/f of 6.5. The curious thing is the shape of the dissociation curve and its strong non-linearity. It is likely that the higher intake manifold temperature (107°F @ 100% diss. vs 75°F @ 0, 30 and 70%) is a contributing factor in the power drop-off at 100% dissociation. These effects of temperature were not observed to occur in the auto tests, but there the mixture ratio was generally much richer, and the engine did not operate satisfactorily without sufficient manifold heating to vaporize at least part of the fuel.

Specific Fuel Consumption

The brake SFC data show greater scatter and have less well defined trends than the power data. Figures 19 and 20 show the basic plots of SFC vs. a/f as functions of nominal dissociation value. A rather peculiar trend reversal is seen for CR = 13, which may be a coincidence of the scatter. The expected monatonic decrease of SFC with increasing CR and a cross plot of SFC against dissociation is shown in Figure 21. The one significant point which is clear in these data is the decreased performance (higher SFC) at the 100% dissociation of pure gas condition. The reason for this decrease is not clear. Furthermore, if these data can be relied upon, it appears that best economy would occur between 50% and 80% dissociation. However, it is easily possible to read more into these results than the lack of precision justifies, so that any evaluation of significant trends must be made with more than the normal degree of caution.

Engine Knock

Engine knock meter readings were taken during the laboratory engine tests to give qualitative knock trends as a function of test variables. No attempt was made to rigorously calibrate the knock meter or measure octane rating of the test fuels. Test data analysis indicated that the engine knock varied considerably with compression ratio, intake air to fuel ratio and percent fuel dissociation. For compression ratios of 13:1, 11:1 and 8.4:1 zero knock meter readings were recorded on all tests except for a few with high dissociation levels and low air-to-fuel ratios. The greatest knock readings were obtained for 100% fuel dissociation at relatively low air-to-fuel ratios, i.e., the knock reading tended to increase with increasing intake fuel concentrations (increasing power) and compression ratios (see Figure 22). Tests 86 through 89 were run specifically to obtain

knock data as a function of dissociation with controlled a/f ratio and RPM, and resulted in increased knock with increasing dissociation. The variation of engine knock with intake manifold temperature (T_2) was not determined in these tests.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Based upon the automotive and laboratory research engine tests described herein, it is concluded that methanol has significant potential as a substitute fuel for reducing automotive air pollution. However, much additional testing and development is required to establish and demonstrate methanol's full potential.

In spite of the limited testing of the methanol fueled automobile and the difficulties encountered, the following observations and tentative conclusions appear to be significant and valid:

1. In two fuel rich tests (37% and 12% fuel rich) unburned hydrocarbons were shown to be 40 PPM and 19 PPM (hexane equivalents) respectively. The trends of these data are regular and reasonable. Furthermore, they appear to be consistent with the widely observed tendency in IC engines for unburned hydrocarbon emissions to decrease as the air/fuel ratio becomes leaner (to a point at which lean misfire, surface ignition, or other combustion irregularities begin to occur). These factors support the conclusion that an engine in which the carburetion and intake manifold system has been optimized for operation with leaner mixture ratios than were used in these tests, will produce less than 20 PPM hydrocarbon emissions.
2. Methanol emissions for the lesser fuel rich condition (12% fuel rich) were 1900 PPM (methanol). Defining this concentration in terms of its hexane equivalents (carbon basis) as is customary with other unconventional fuels such as natural gas and liquid petroleum gases,

the methanol emissions become 317 PPM or a total of 336 PPM hydrocarbons plus methanol (not including aldehydes). This compares favorably with the value of 341 PPM (hexane equivalents) reported by ARL for the Dodge Dart with gasoline. Using the same arguments as in Item 1, above, and considering the more comprehensive data from the CFR lab tests, it is concluded that significant reductions in methanol emissions can be achieved through operation with leaner mixture ratios and with a more optimum carburetion and intake manifold heating system.

3. Reduction of CO emissions to 1970 requirement appears to be attainable.

4. Formaldehyde (and probably total aldehyde) emissions are higher than from gasoline fueled engines, and need more intensive investigation.

5. Additional carburetion and intake manifold heating development will be required to assure good cold start performance and uniform cylinder mixture distribution and performance.

Within their limited scope, the following factors were indicated by the single cylinder research engine tests:

1. Unburned methanol and aldehyde emissions may be virtually eliminated by complete methanol predecomposition or reforming. Emission pollutant concentrations decreased monatonically with increased dissociation.

2. Methanol and formaldehyde emissions maximized at a compression ratio of approximately 13:1.

3. Minimum brake specific fuel consumption was obtained for dissociation levels of 70% and for lean a/f ratios.

4. Methanol emission levels with manifold heating were minimized for values near the chemically correct a/f ratio for complete combustion. Formaldehyde emission levels were minimized at fuel rich a/f ratios.
5. Methanol and formaldehyde emission concentrations were significantly reduced by intake manifold mixture heating.
6. Engine knock increased with methanol dissociation level, becoming most severe at 100% dissociation.

To establish the full potential of methanol as a substitute fuel and to more clearly define areas which require further development, the following work is recommended:

1. A detailed evaluation of the emission and performance characteristics of several auto engines, with high and low compression engines.
2. Optimization of a/f, manifold temperature, and spark timing over the full range of throttle and RPM conditions to produce minimum emissions with acceptable power output and economy.
3. Road tests of these engines over an extended period to determine wear and corrosion problems and their effects of engine operating variables on emission levels and performance.
5. Development of laboratory and auto engine reforming hardware.

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3. Federal Register, Dept. of HEW, "Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines", Volume 33, Number 108, Dart II, June 1968.

4. Emission Test for CETEC Gasoline vs. Methanol, Project M196, California Air Resources Board, Air Resources Laboratory, July 1969.

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6. J. A. Bolt, E. S. Starkman, H. K. Newhall, R. D. Sutton, G. C. Lawrason, P. F. Finigan, M. W. Jackson, "Alcohols and Hydrocarbons as Motor Fuels," S.P. 254, Society of Automotive Engineers.

7. ASTM-CFR Fuel Testing Units, Waukesha Motor Co.

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Table I. Chrysler Motor Corporation
225 cu. in. Six Cycle Engine Specifications

Horsepower	145 @ 4000 rpm
Torque, ft-lb.	215 @ 2400 rpm
Bore, in.	3.40
Stroke, in.	4.125
Compression Ratio	8.4:1

Table II. LA-2 Course Mileage Breakdown

Type Driving	Approximate Miles
Downtown	4
Freeway	6
Residential	5
Boulevard	10
Total	25

Average Speed = 16 - 18 mph

Total L. A. mileage on course during gasoline emission tests - 403

Table III. Gasoline Exhaust Emission Automotive Data Summary

Air Resources Laboratory

Test Fuel _____ Basin Mix Gasoline

Test Date	Test No.	Exhaust Emissions: Continuous Sample (Ave) *HC ppm	CO, %	NO, ppm	Bag Sample (Raw) *HC ppm	CO, %	NO, ppm
5-13-69	1	307	2.07	1135	301	1.95	3534
5-15-69	2a	370	2.19	1160	333	2.33	3019
5-16-69	3	297	1.70	2632	408	2.50	5157
5-19-69	4	349	2.20	1168	336	2.21	2932
5-20-69	5	384	2.47	1219	395	2.41	-
	Average	341	2.13	1463	355	2.28	3660

* Hexane Equivalent

Table IV. Methanol Exhaust Emission Automotive Data Summary

Air Resources Laboratory

Test Fuel _____ Methanol

Test Date	Test No.	Exhaust Emissions Continuous Sample Ave. HC, ppm	CO %	NO, ppm	Aldehydes ppm	Bag Sample HC, ppm	CO, %	NO, ppm	Main Jet Dia. In.	Air Corr. Jet Dia. In.
7-15-69	6	2563	4.14	637	108	1654	4.42	1324	0.064	0.064
7-16-69	7	1671	4.13	1118	123	632	3.46	1340	0.064	0.064
7-17-69	8	1869	5.60	264	-	864	6.19	882	0.070	0.087
7-18-69	9	1533	6.36	277	166	748	6.36	365	0.073	0.087
	Average	1909	5.05	574	132	974	5.11	978		

Note: HC (including methanol) in PPM Hexane

Table V. Methanol Exhaust Air to Fuel Ratio, Hot Cycle Average*

ARL Test No.	Carburetor Config. Main Jet Dia. In.	Air Corr. Jet Dia. In.	Air to Fuel Ratio** Continuous Sample Idle	15 mph	30 mph	15-30 mph	30-15 mph	Bag (GC)
6	0.064	0.064	6.23	5.49	5.60	5.98	5.51	5.91
7	0.064	0.064	5.83	5.58	5.57	5.79	5.57	5.99
8	0.070	0.087	5.80	5.26	5.36	5.65	5.36	5.80
9	0.073	0.087	6.16	5.48	5.28	5.55	5.42	5.67

* Calculated assuming negligible O_2 in exhaust

** Air to Fuel Ratio for chemically complete combustion of methanol is 6.49

Table VI. Exhaust Analysis by GC

Compound	ppm Compound
Methane	105
Ethane	2
Ethylene	38
Acetylene	30
Propylene	10
Methy Acetylene*	60-150
Iso-pentane	3
N-pentane	2
Methanol**	900
Total	1150-1240

* Identified and determined by retention time, peak comparisons comparisons and logic.

** 900 ppm of Nitro-Methane was reported by ARL but it is believed to have been unburned methanol, although it may have been possible for nitro-methane to have formed in the undiluted exhaust sample while in the bag.

Table VII. Average Cold Start 7 Mode Cycle Emission Data
(Chevron Research Company[5])

	0.070 Main Jets			0.063 Main Jets		
	gm/mile	PPM*	Percent	gm/mile	PPM	Percent
Unburned Methanol	12.5	4300	-	5.1	1900	-
Unburned Hydrocarbons	0.06	40	-	0.03	19	-
CO	148	-	6.1	50	-	2.1
Formaldehyde			-	0.3	110	-
NO_x	**	**	-	4.3	1050	-

* Methanol as Methanol, HC as Hexane, Formaldehyde as Formaldehyde

** Data Questionable

Table VIII. Cylinder Distribution Data*
(Chevron Research)

	CO, %	NO_x, PPM	CO, %	NO_x, PPM	CO, %	NO_x, PPM
0.070 Main Jet - 15 mph	10.0	120	9.2	110	8.6	140
55 mph	8.5	180	5.5	440	4.1	1000-1200
0.063 Main Jet - 15 mph	6.7	140	6.4	130	4.2	152
55 mph	2.7	650	1.6	1150	0.4	2250

*Only CO and NO_x measured

Table IX. Temperature Data

1. Intake manifold temperature (carburetor side)*
2. Intake manifold temperature (engine side)*
3. Water into engine heat exchanger
4. Water out of engine heat exchanger
5. Fuel flow metering system inlet gas temperature
6. Gaseous fuel flow metering system outlet gas temperature
7. Air flow meter inlet temperature
8. Exhaust sample temperature
9. Oil temperature
10. Ice temperature (Ref. Temperature)
11. Ice temperature (Ref. Temperature)
12. Ambient temperature
13. Exhaust temperature

*Heater element in intake manifold.

Table X. Laboratory Engine Test Matrix

Run	Compression Ratios	Nominal Air-to-Fuel Ratios+	Timing Deg. BTDC	Manifold Heating	Nominal Dissociation, %	Objective
1-29	8.4:1, 11:1, 15:1	5.5-9.0	Var.	Var.	0, 30	General checkout, Engine Performance and Operation Mapping
30-35	15:1	5.5, 6.5, 7.5, 9.0	14-22	Yes-No	0	Determine effect of A/F ratio and manifold heating on emissions and performance at constant dissociation and compression ratio
36-44	8.4:1, 11:1, 13:1	5.5, 6.5, 7.5	13-15	Yes	0	Determine effects of A/F and compression ratio on emissions and performance at zero dissociation with manifold heating.
45-52	11:1, 15:1	5.5, 6.5, 7.5, 9.0	15	Yes	30	Determine effects of A/F and compression ratio on emissions and performance of 30% dissociation with manifold heating.

Table X (continued)

Run	Compression Ratios	Nominal Air-to-Fuel Ratios+	Timing Deg. BTDC	Manifold Heating	Nominal Dissociation, %	Objective
53-60	11:1, 15:1	5.5, 6.5, 7.5, 9.0	10	Yes	70	Determine effects of A/F and compression ratio on emissions and performance at 70% dissociation with manifold heating.
61-78	11:1, 13:1, 15:1	5.5, 6.5, 7.5, 9.0	10	Yes	100	Determine effects of A/F and compression ratio on emissions and performance at 100% dissociation with manifold heating.
79-91	8.4:1, 13:1, 15:1	5.5, 6.5, 7.5, 9.0	10	Yes		Obtain additional data to fill in text matrix from previous tests. Two tests were run to determine the effects of water addition on engine performance.

+ Nominal or planned Air-to-Fuel Ratio varied considerably from actual A/F when test data was reduced.

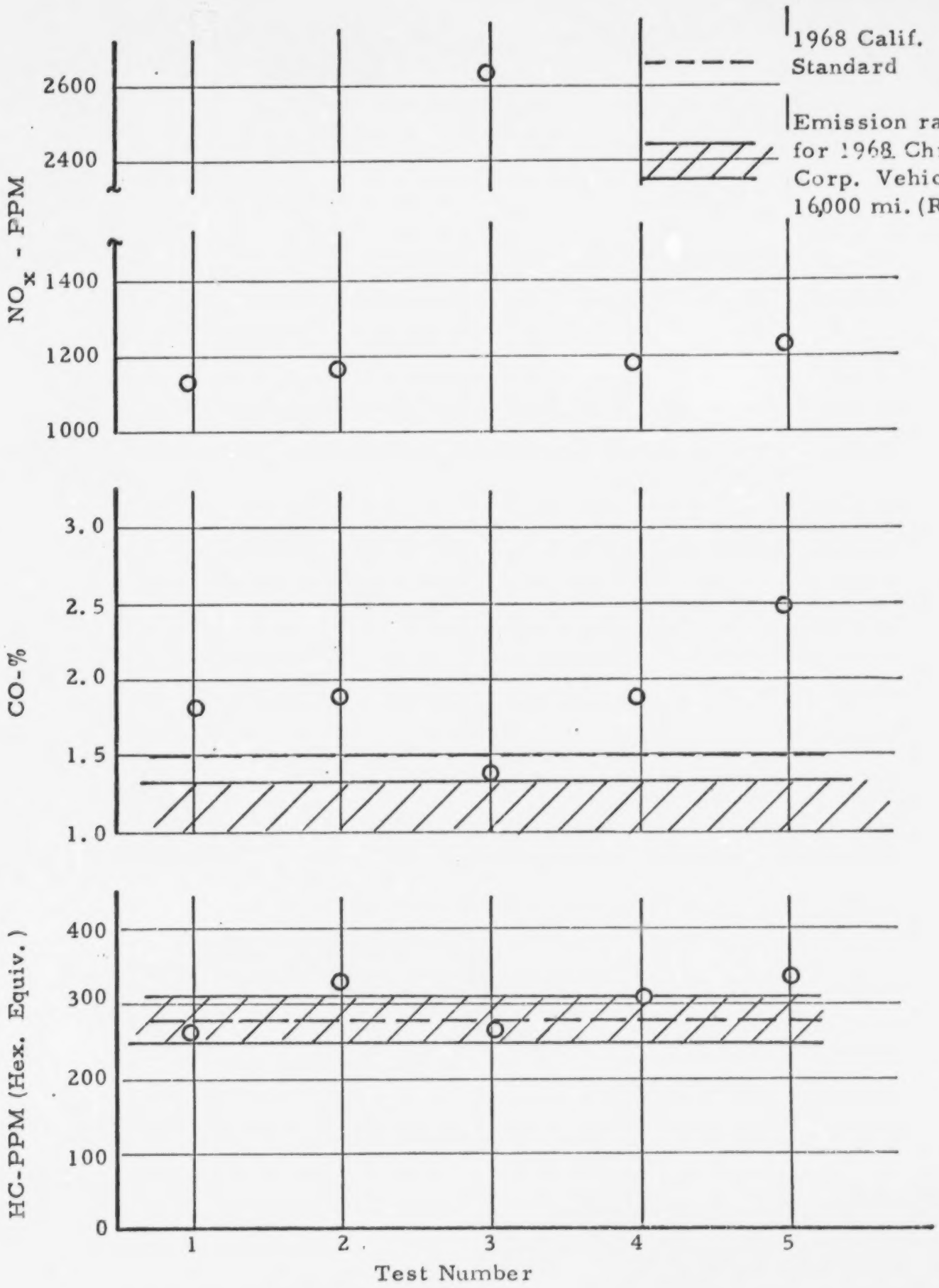
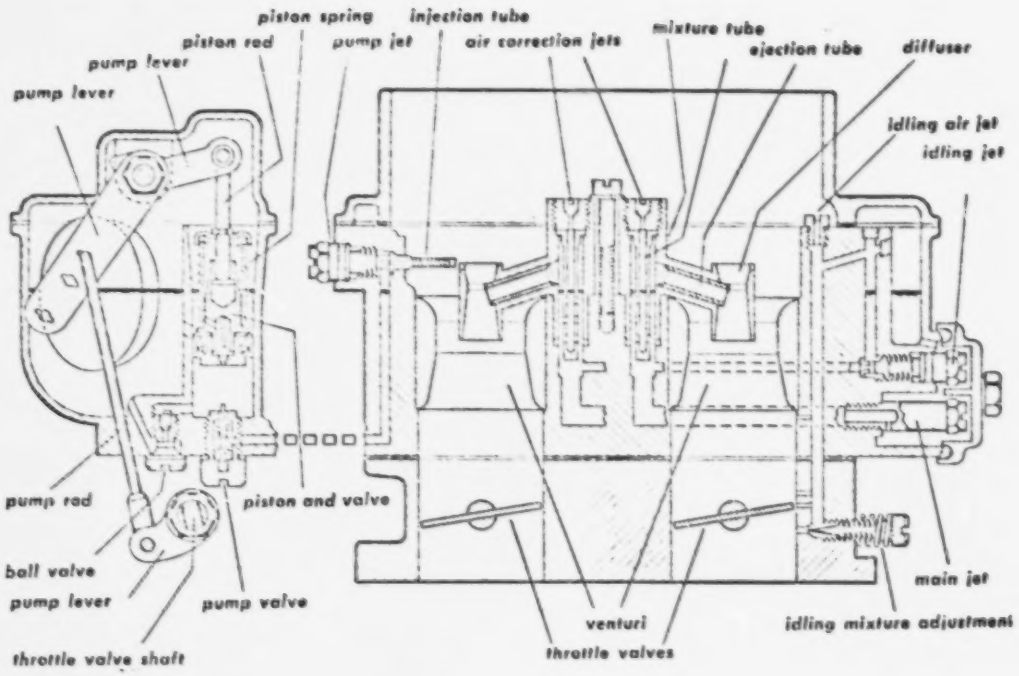
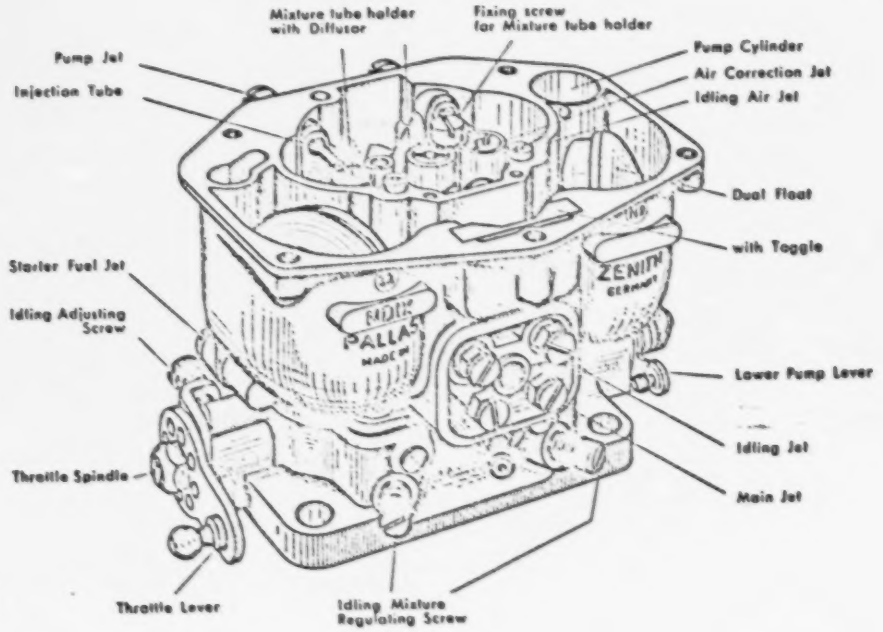


Figure 1. Average Hot Cycle (Nos. 6 & 7) Emissions - Dodge Dart with Gasoline (ARL Tests)





The dual-throat Zenith NDIX carburetor

Exploded view of the Zenith 32 NDIX carburetor

NOT REPRODUCIBLE

Figure 2. Zenith 32 NDIX Carburetor Construction

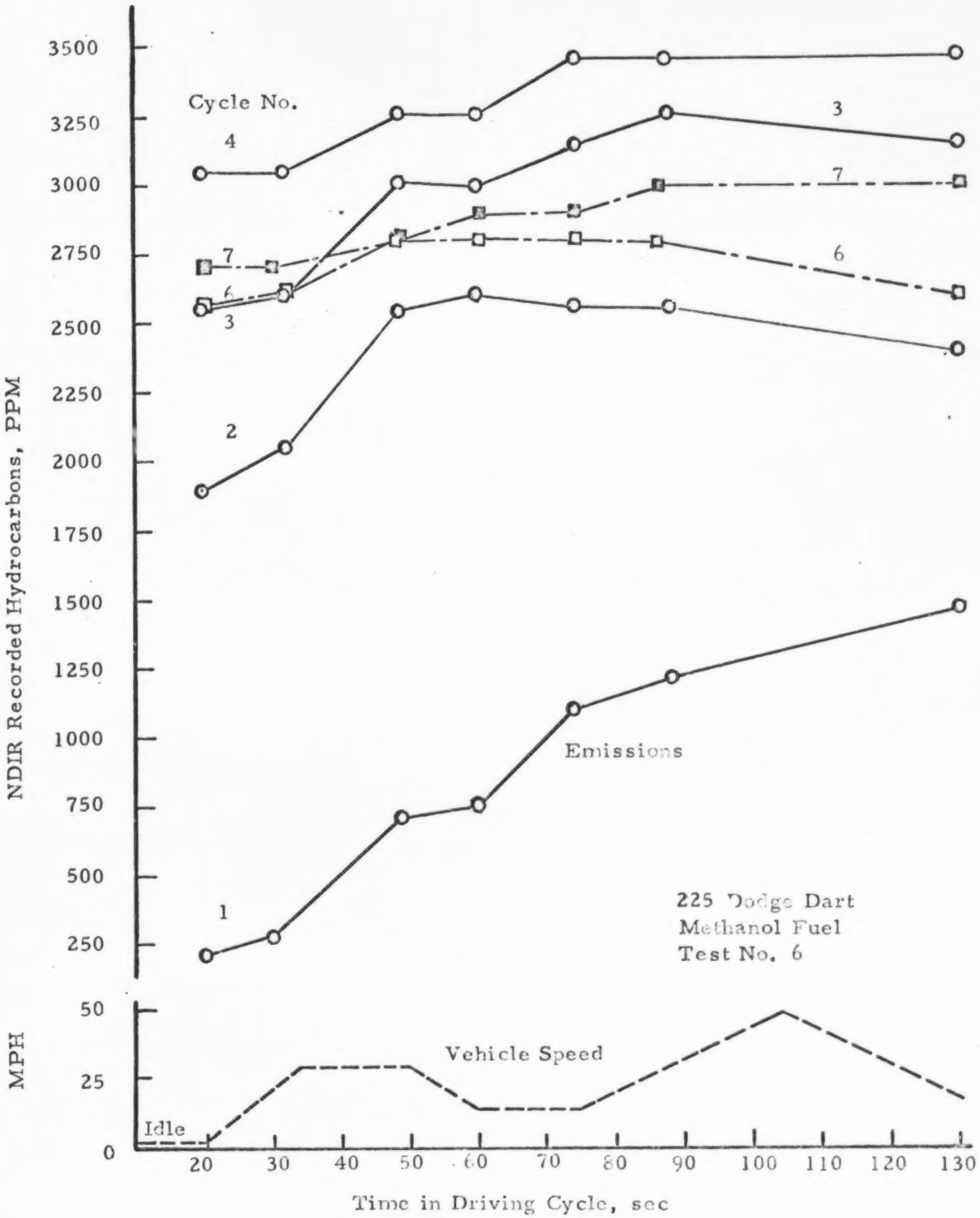


Figure 3. Measured Hydrocarbon Emissions as a Function of Time and Cycle

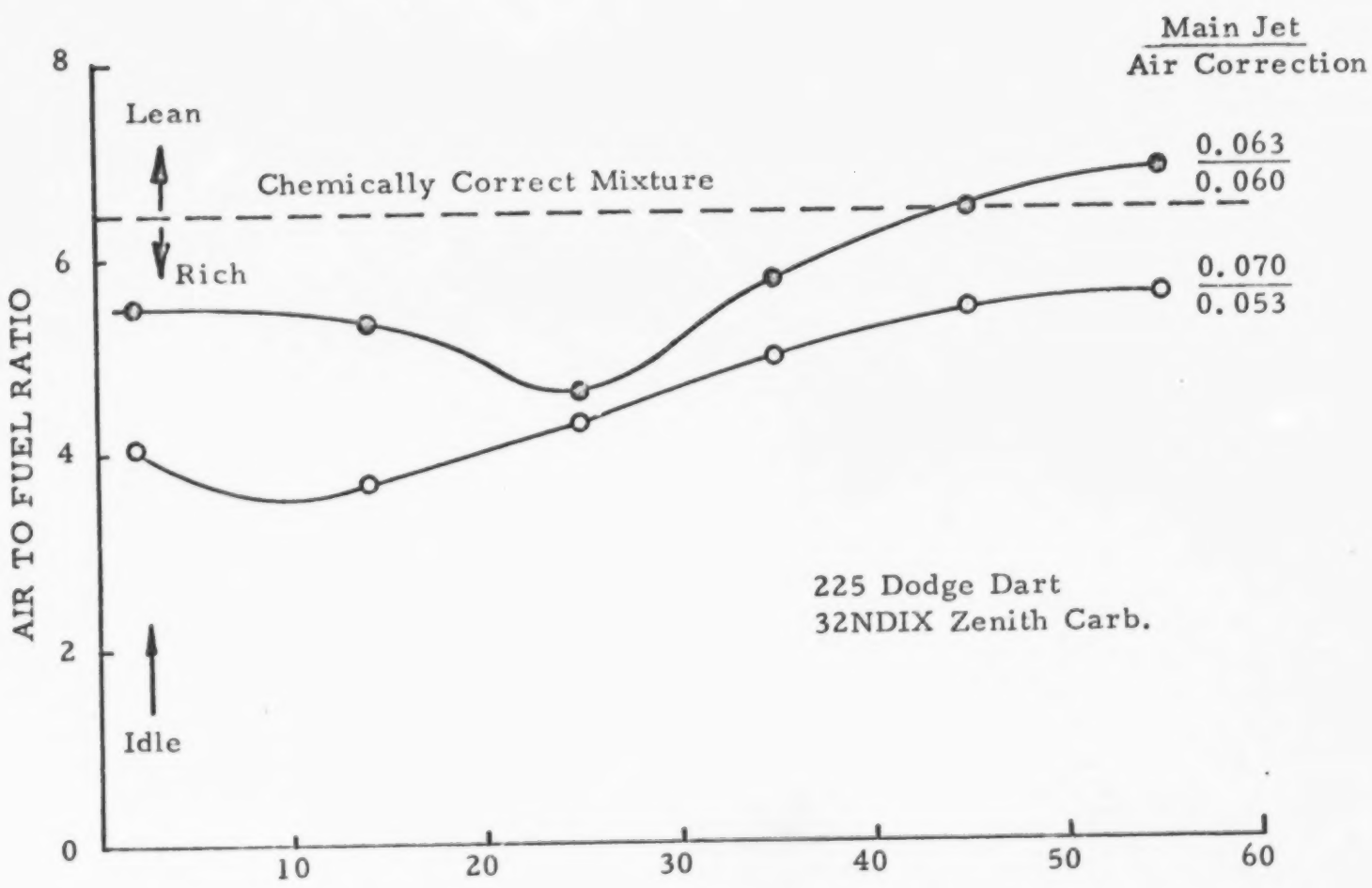


Figure 4. Air to Methanol Mixture Ratio as a Function of Speed

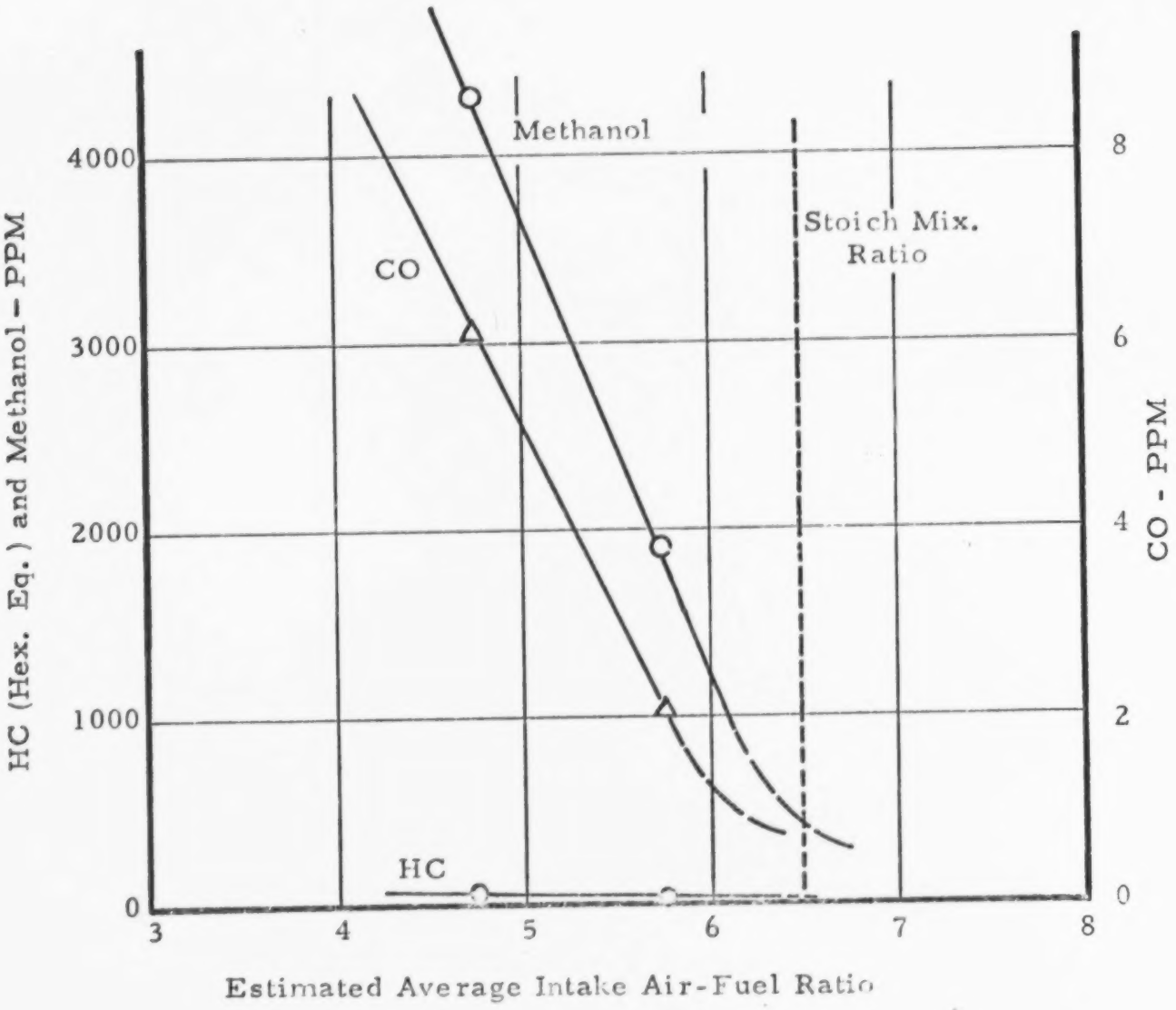


Figure 5. Average Emissions, Federal Seven Mode Cycle (Chevron Tests)

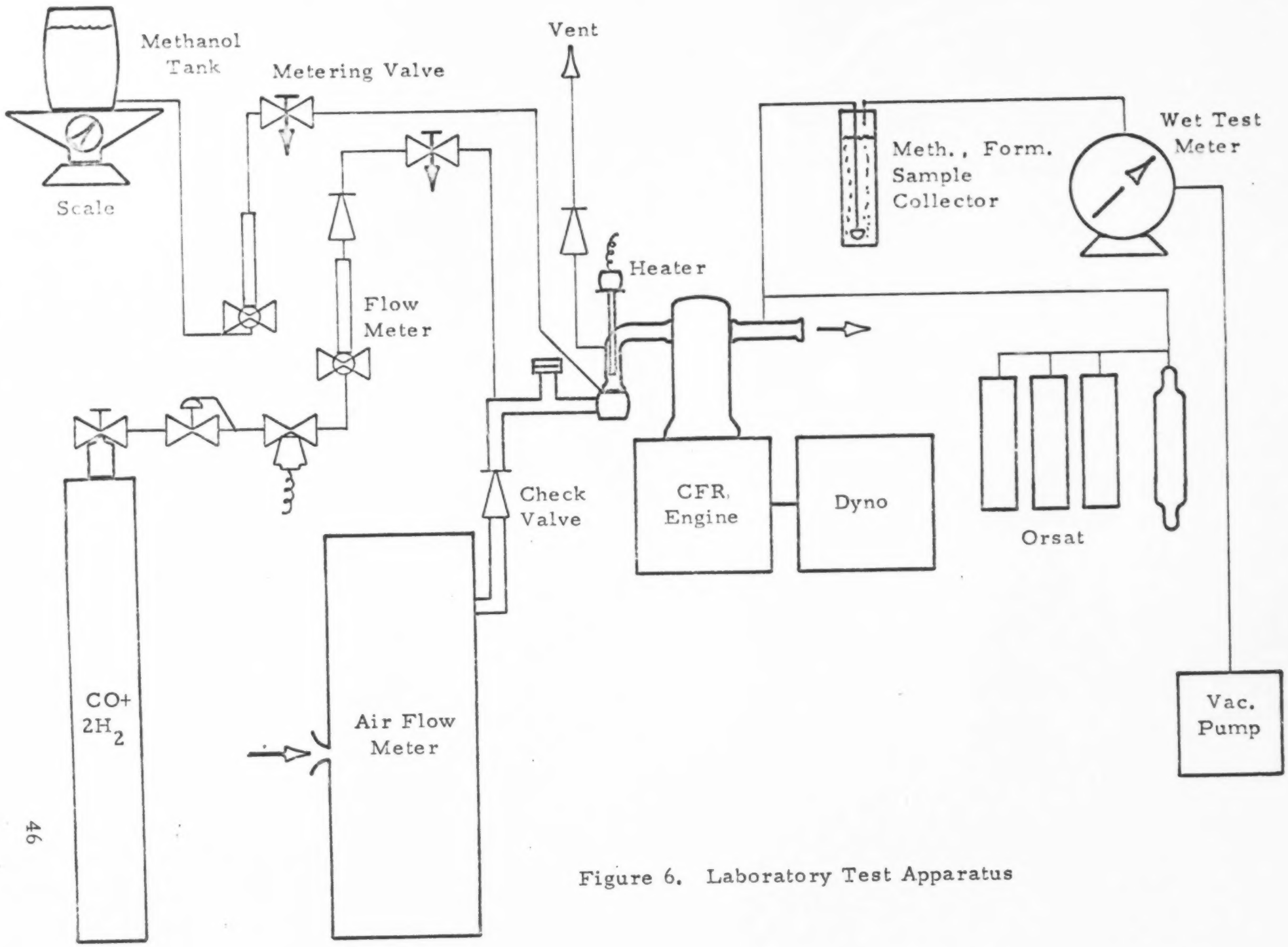


Figure 6. Laboratory Test Apparatus

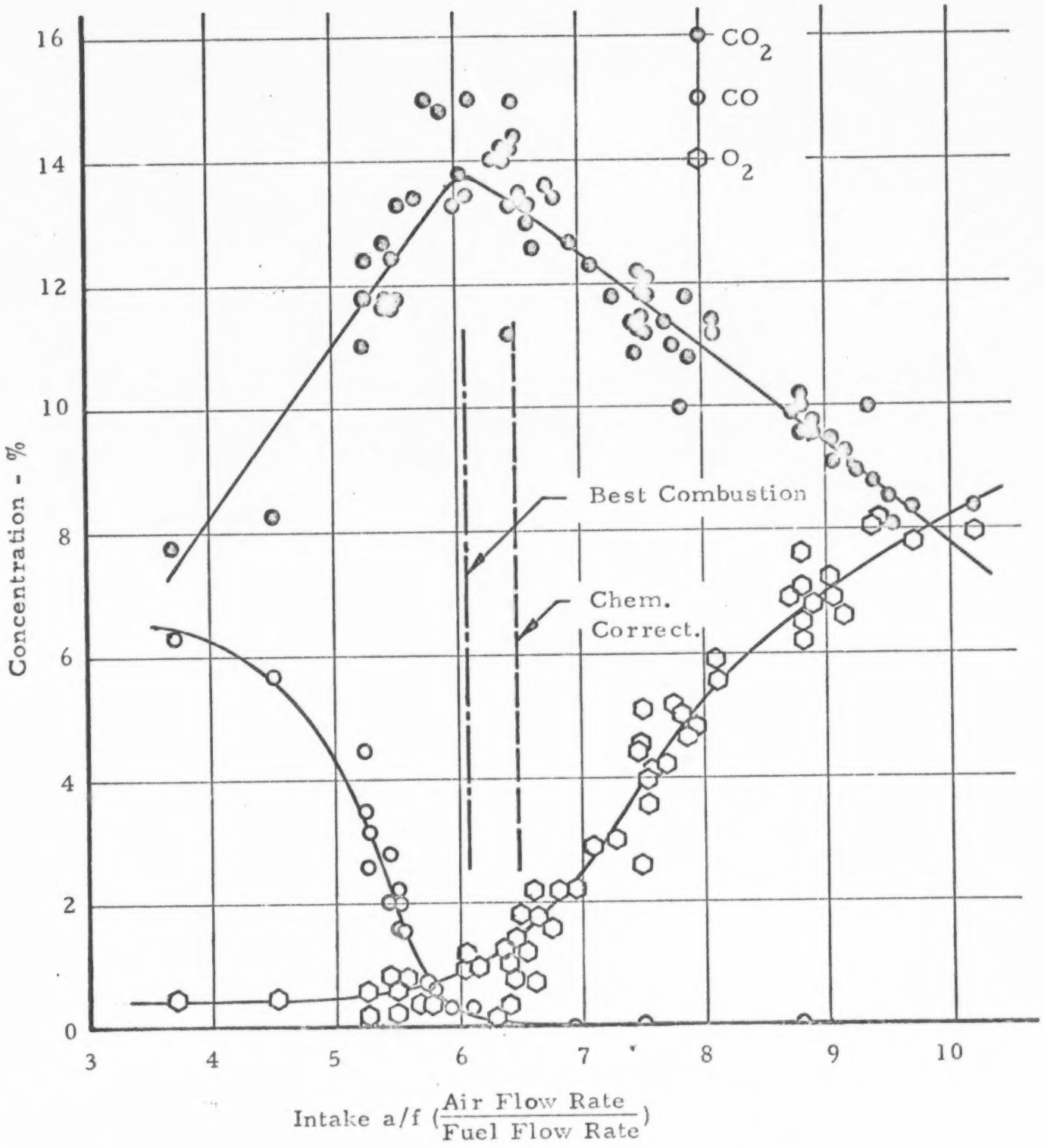


Figure 7. CFR Engine CO_2, CO, and O_2 Emissions

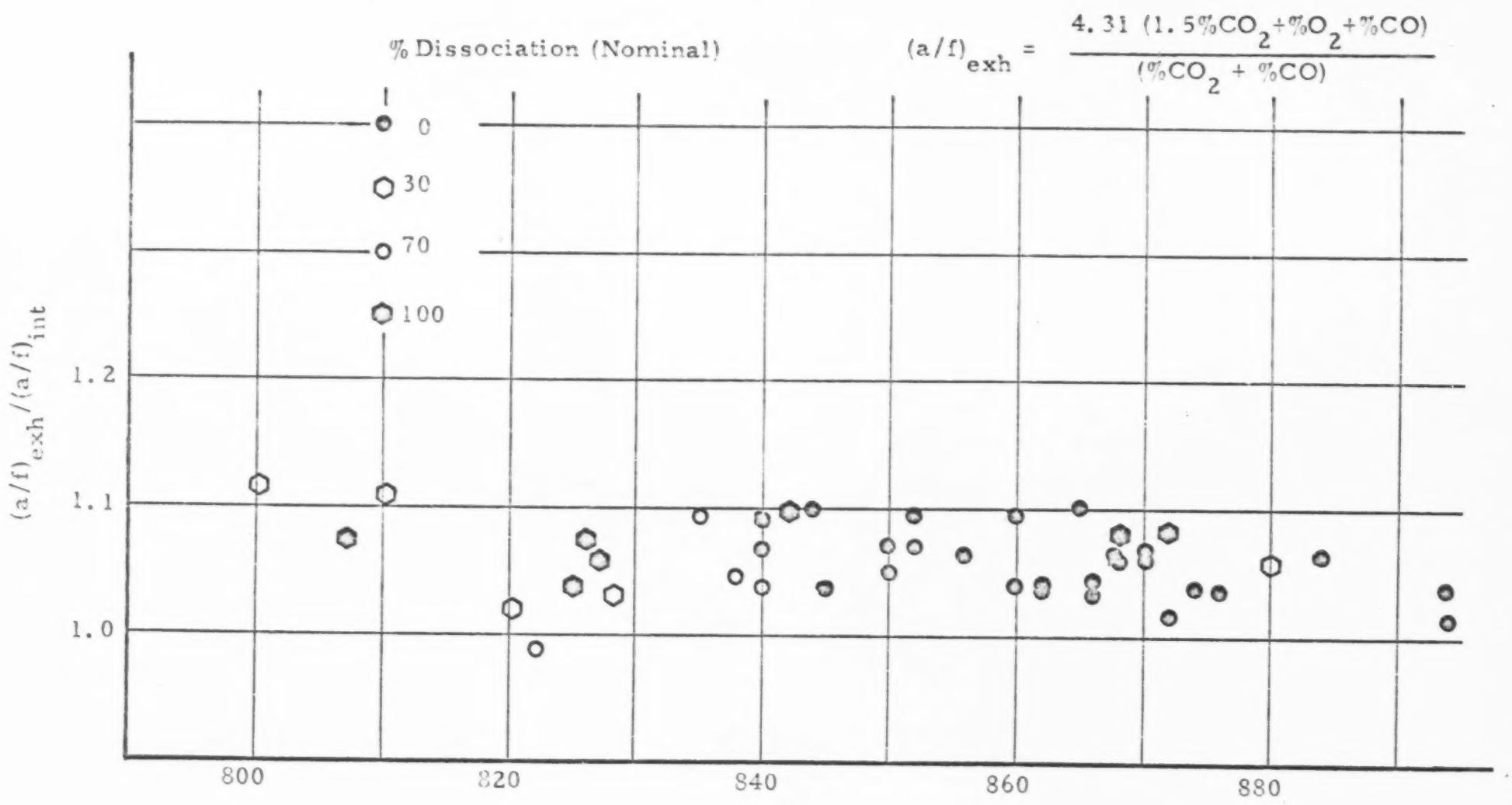


Figure 8. Ratio Between Calculated Exhaust and Measured Intake Air-Fuel Ratios

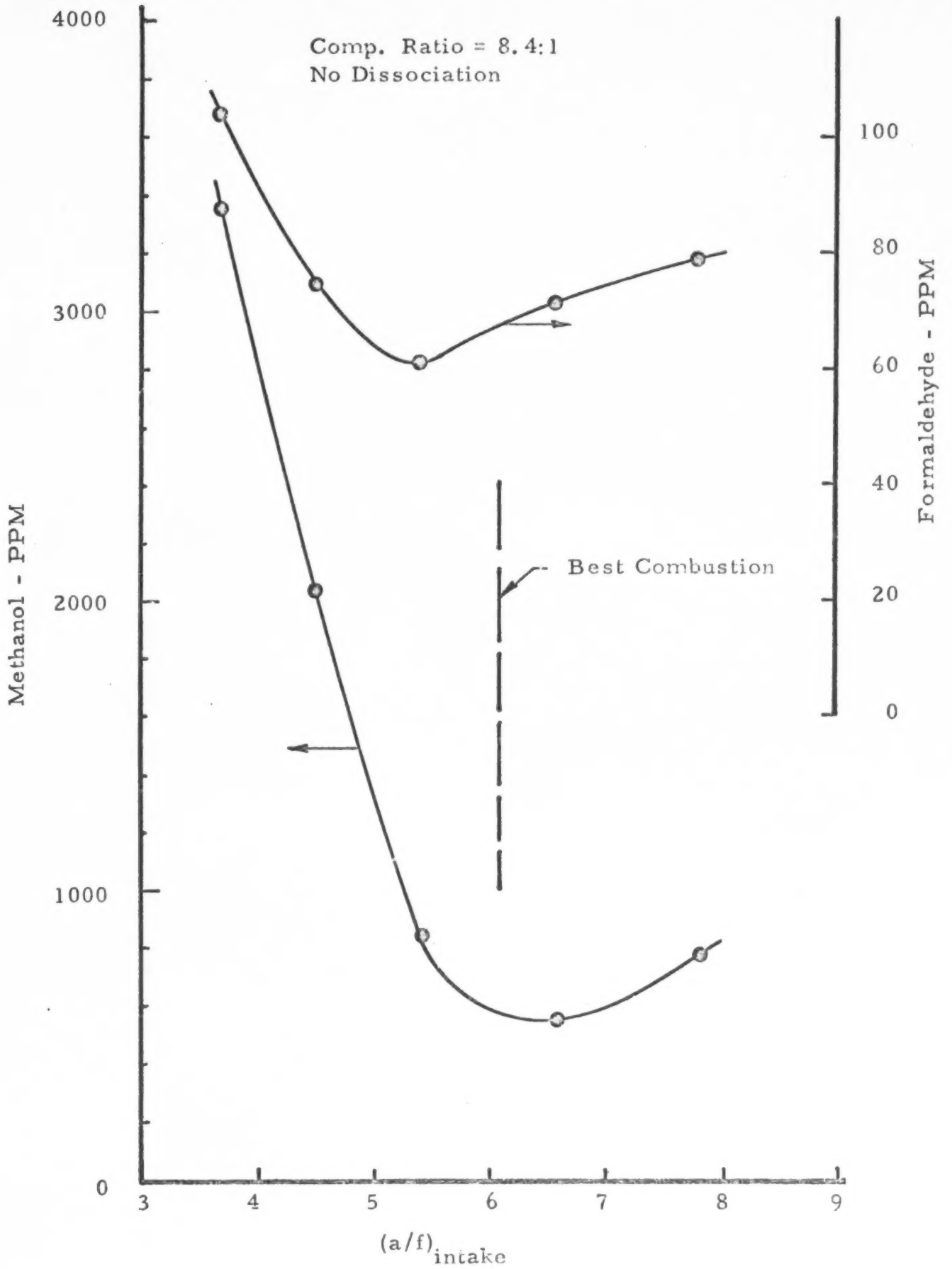


Figure 9. CFR Engine Emissions

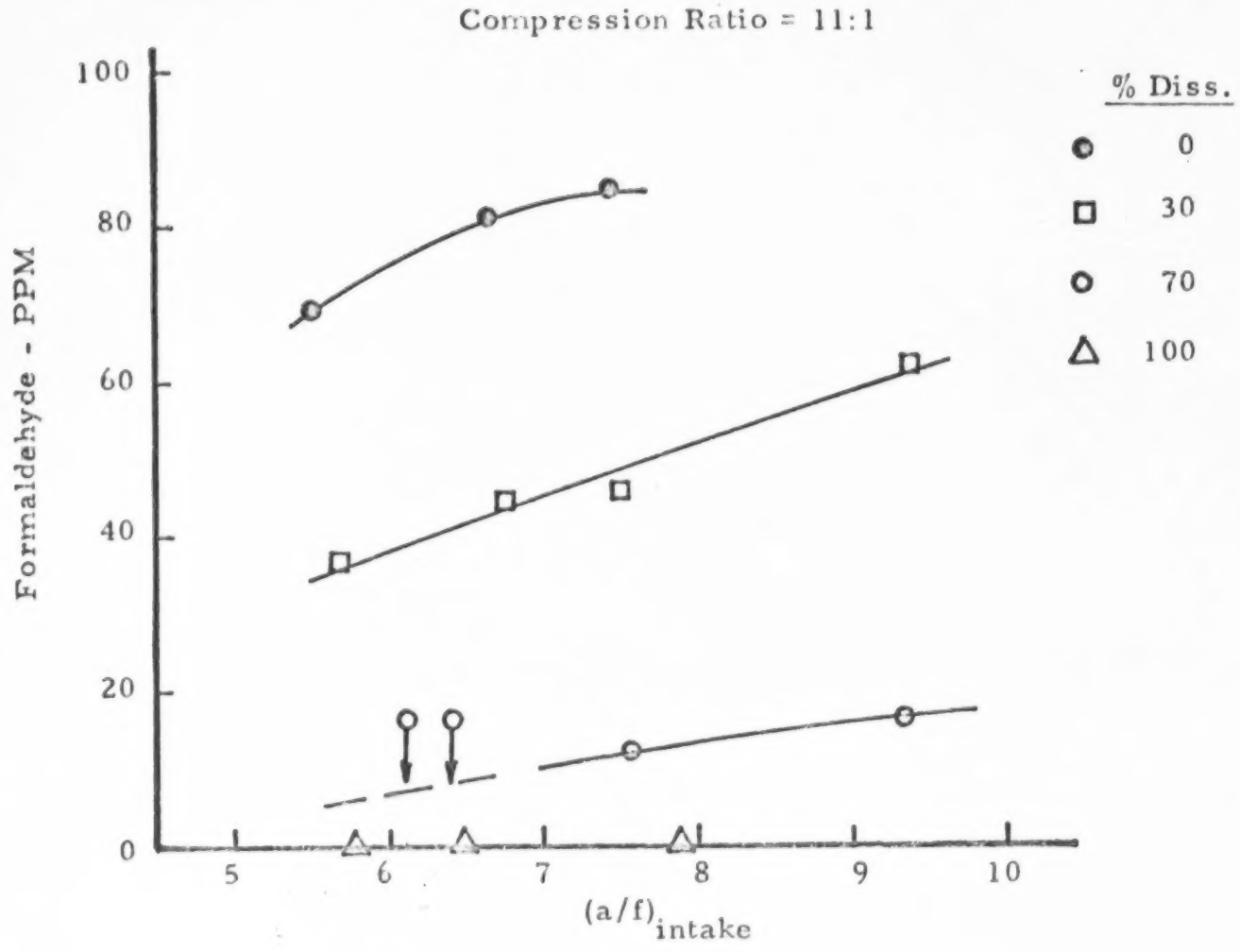


Figure 10. CFR Engine Emissions

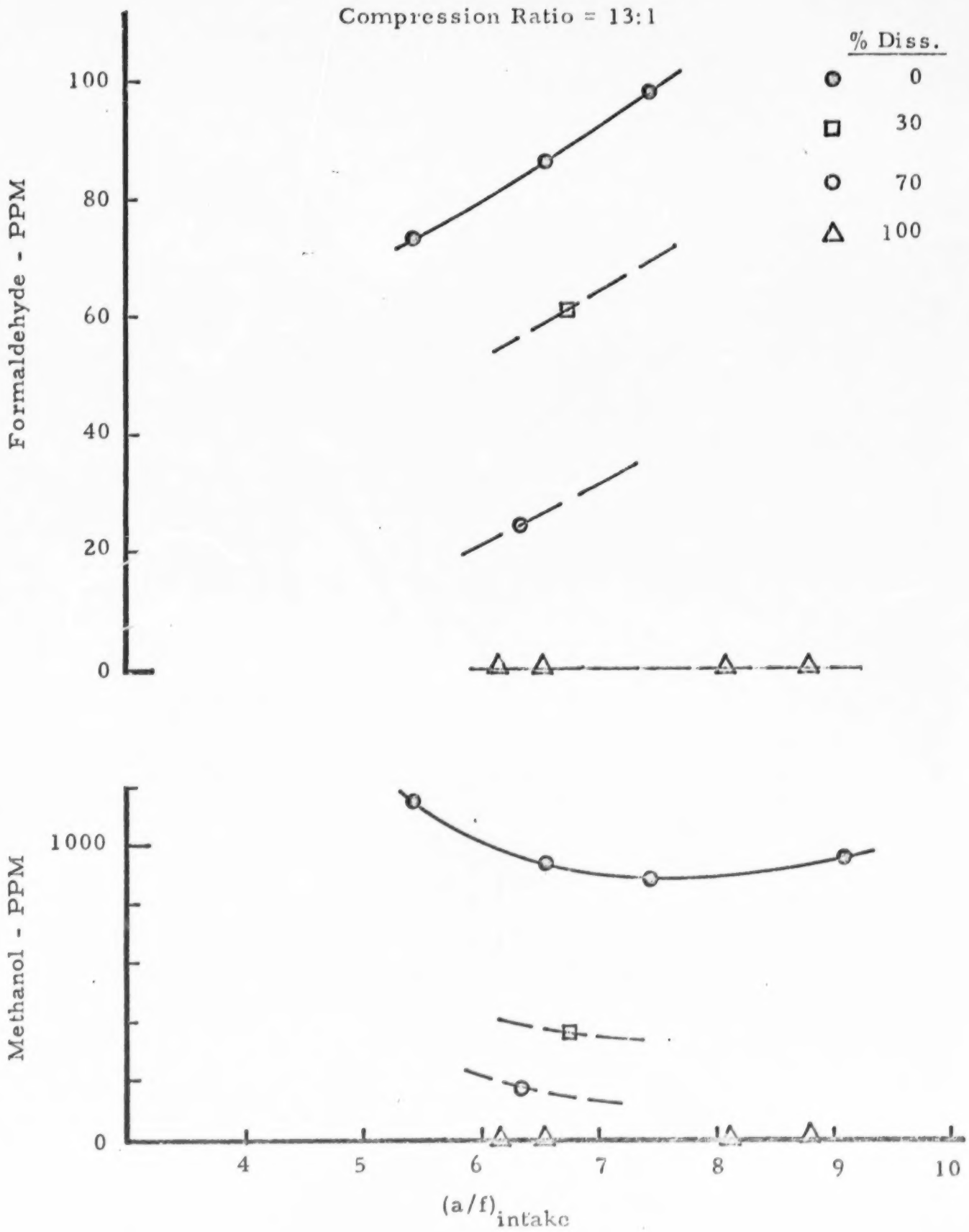


Figure 11. CFR Engine Emissions

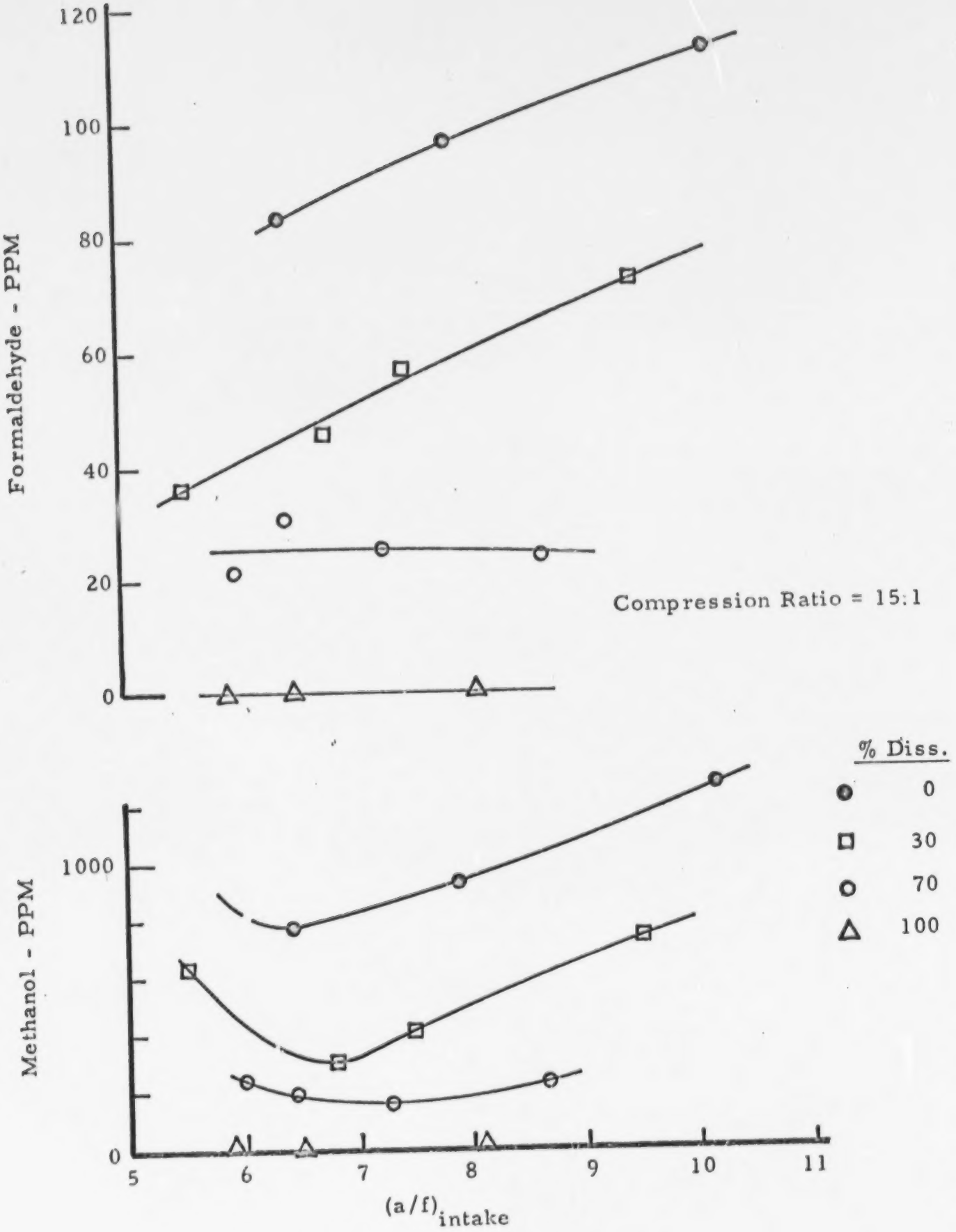


Figure 12. CFR Engine Emissions

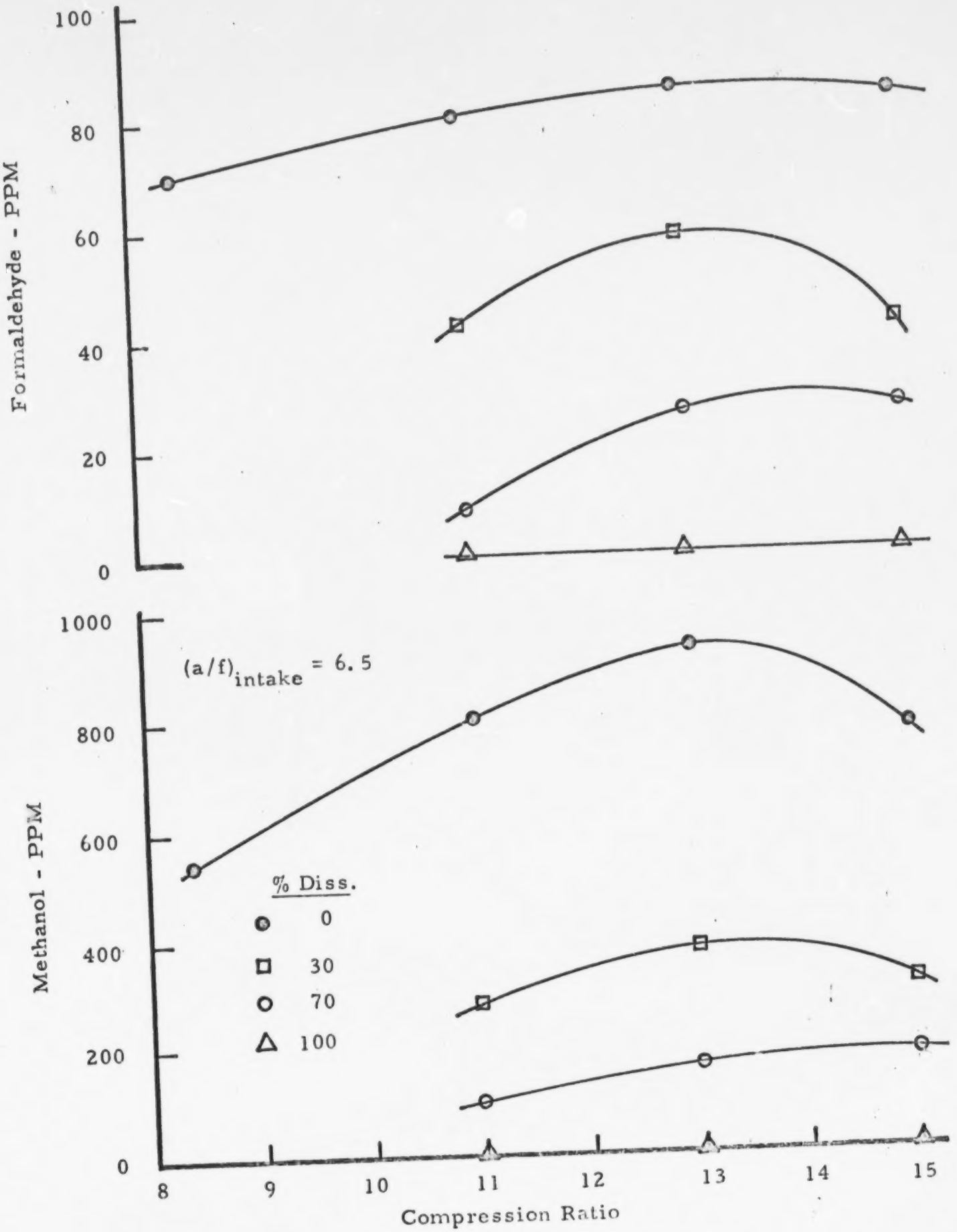


Figure 13. Effect of Compression Ratio on Emissions

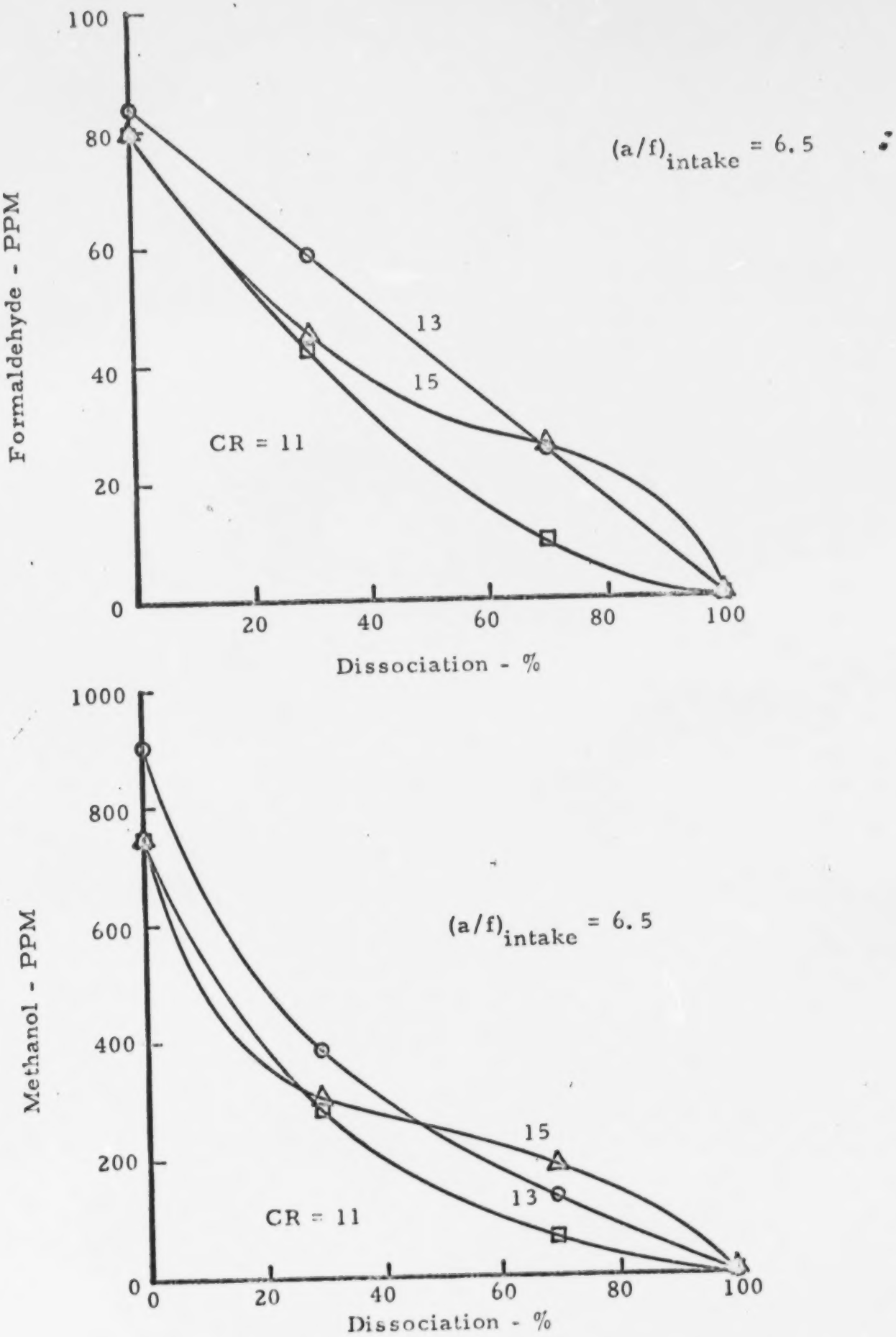


Figure 14. Effects of Methanol Dissociation Level on CFR Engine Emissions

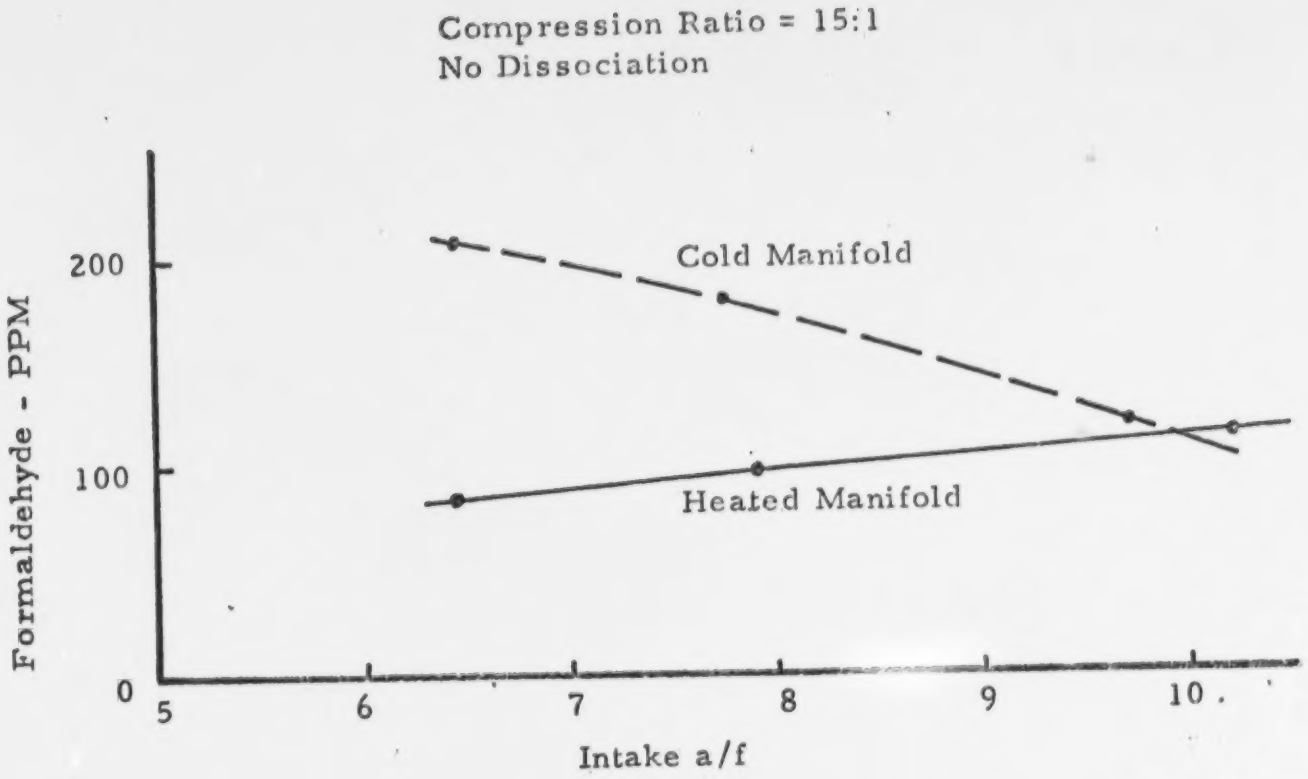
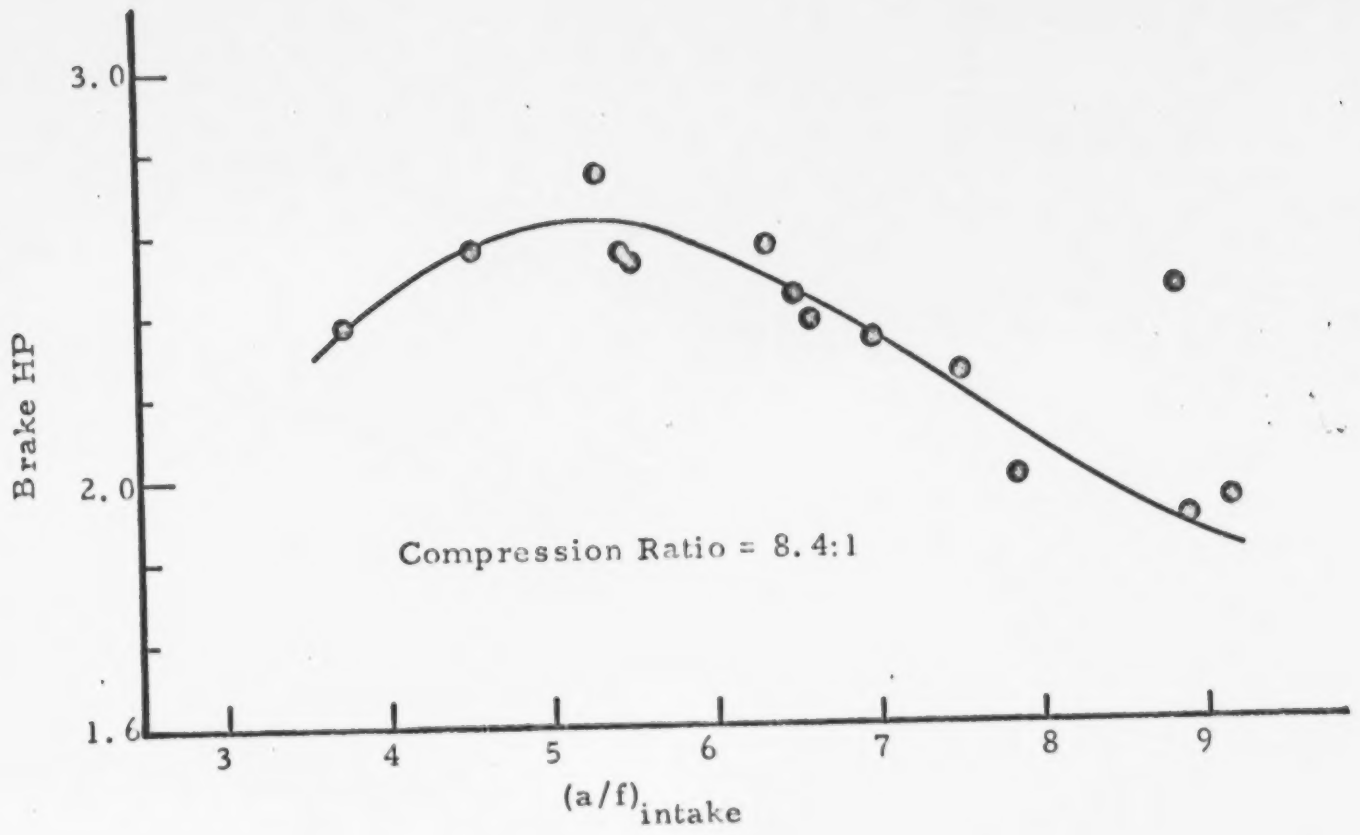


Figure 15. Effects of Manifold Heating on Emissions



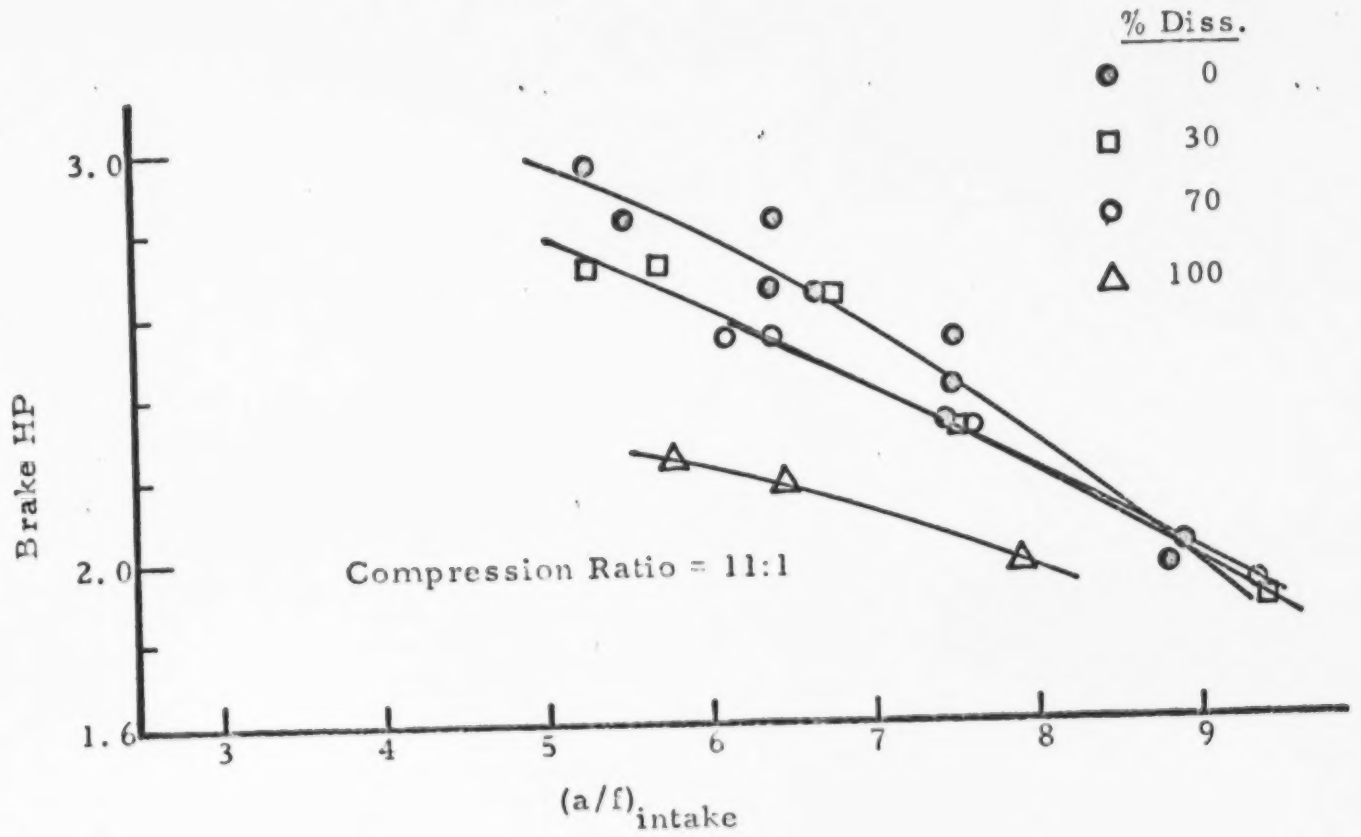
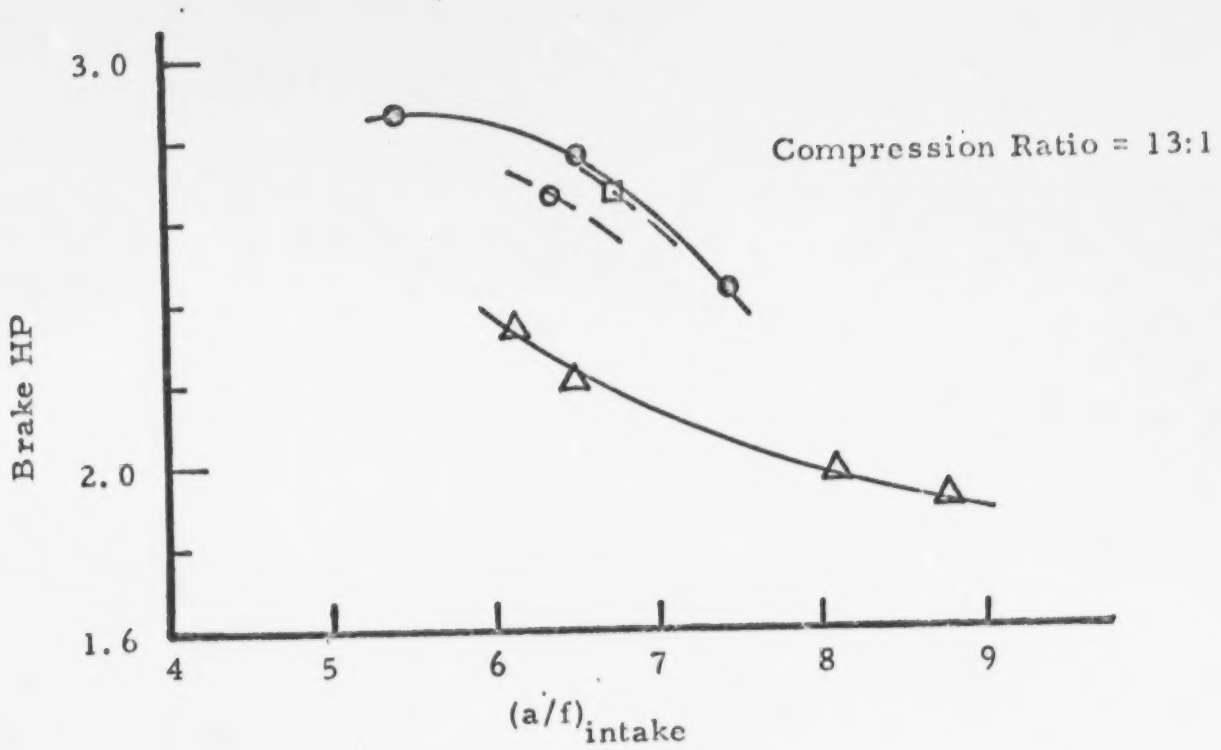


Figure 16. CFR Engine Power Output,
CR = 8.4:1, 11:1



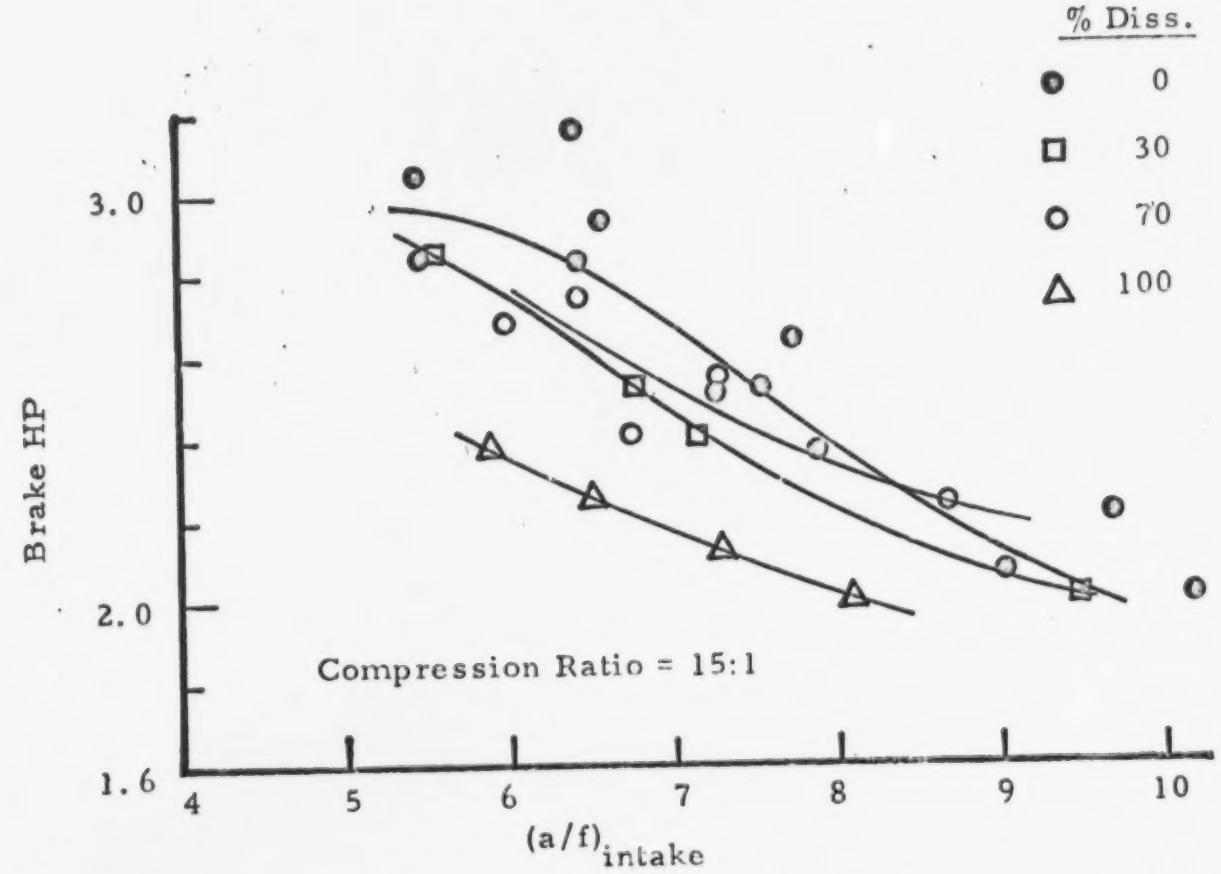
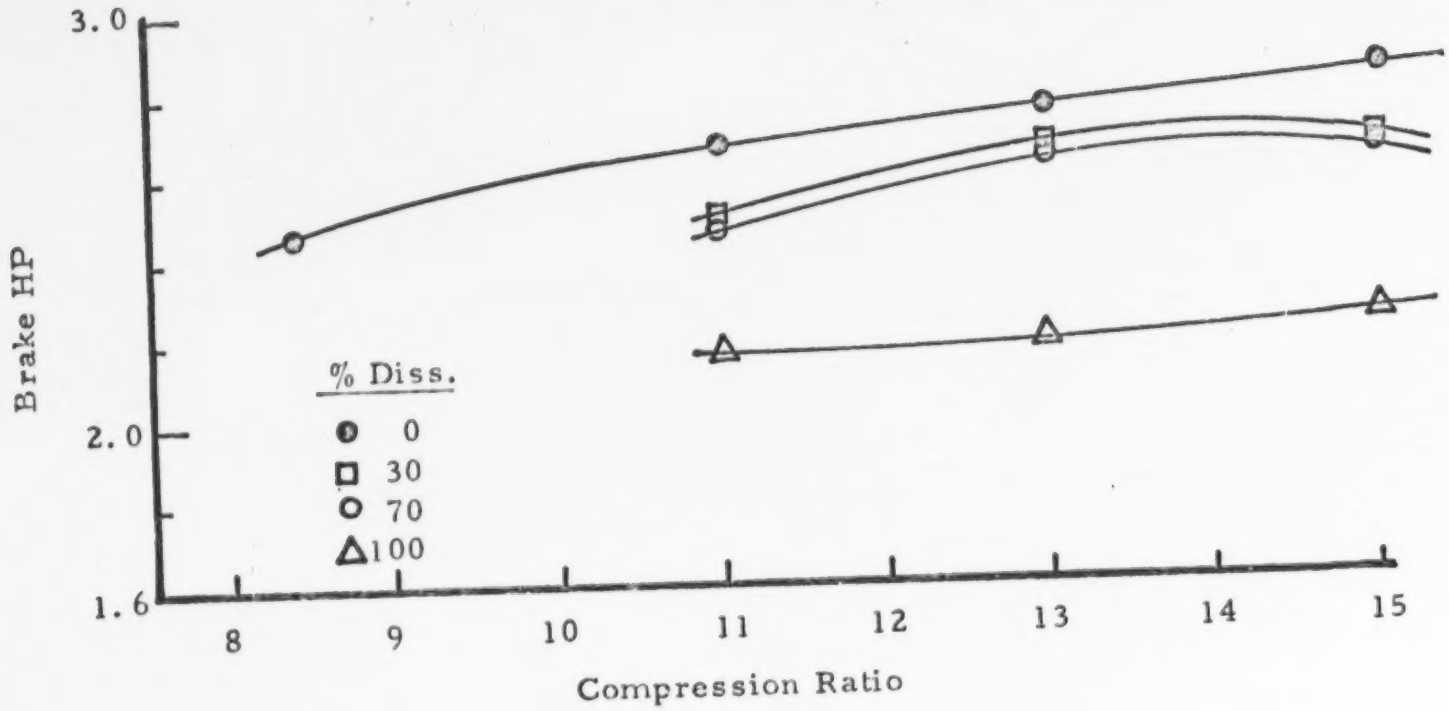


Figure 17. CFR Engine Power Output, CR = 13:1, 15:1



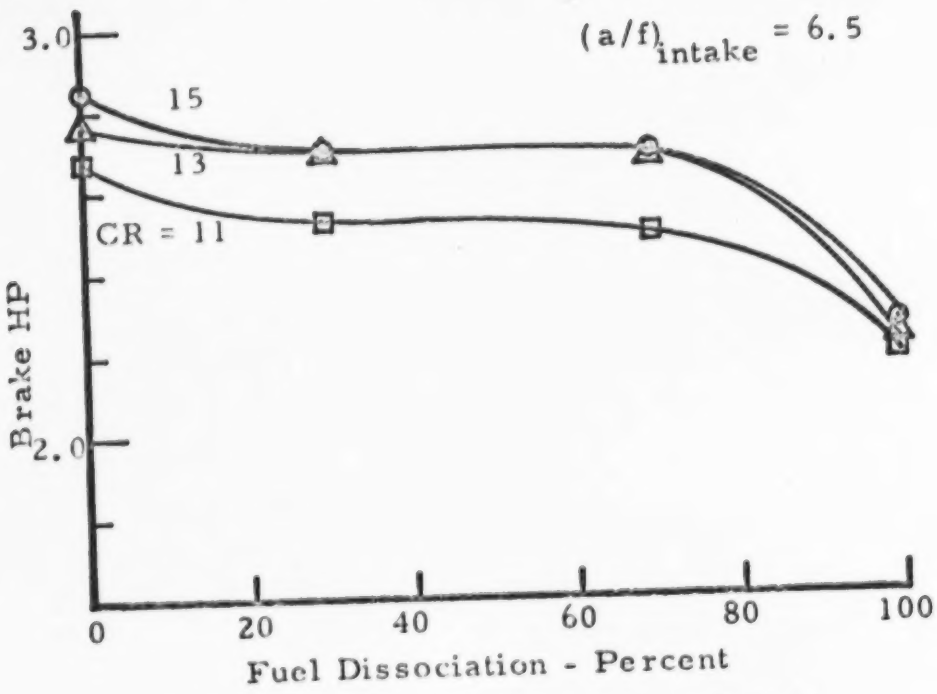
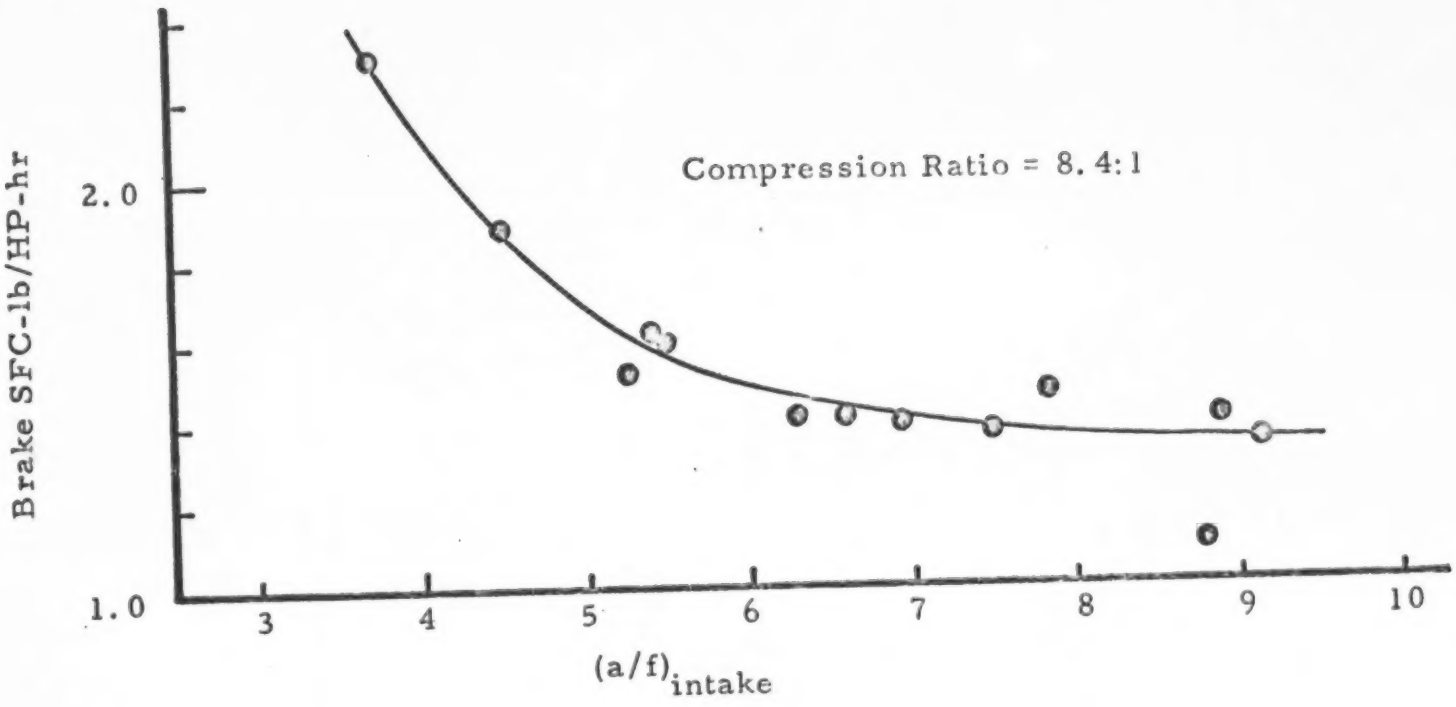


Figure 18. CFR Engine Power Output



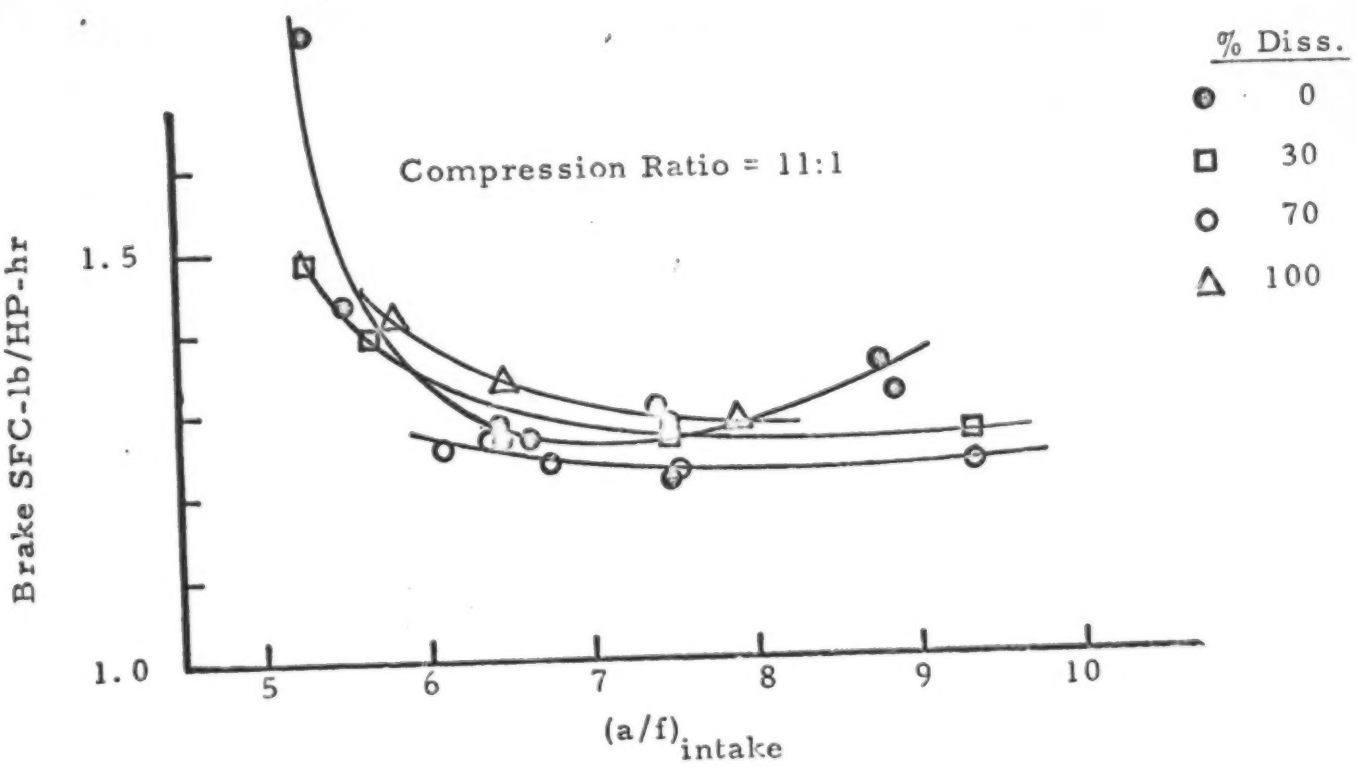


Figure 19. CFR Engine Fuel Consumption, CR = 8.4:1, 11:1

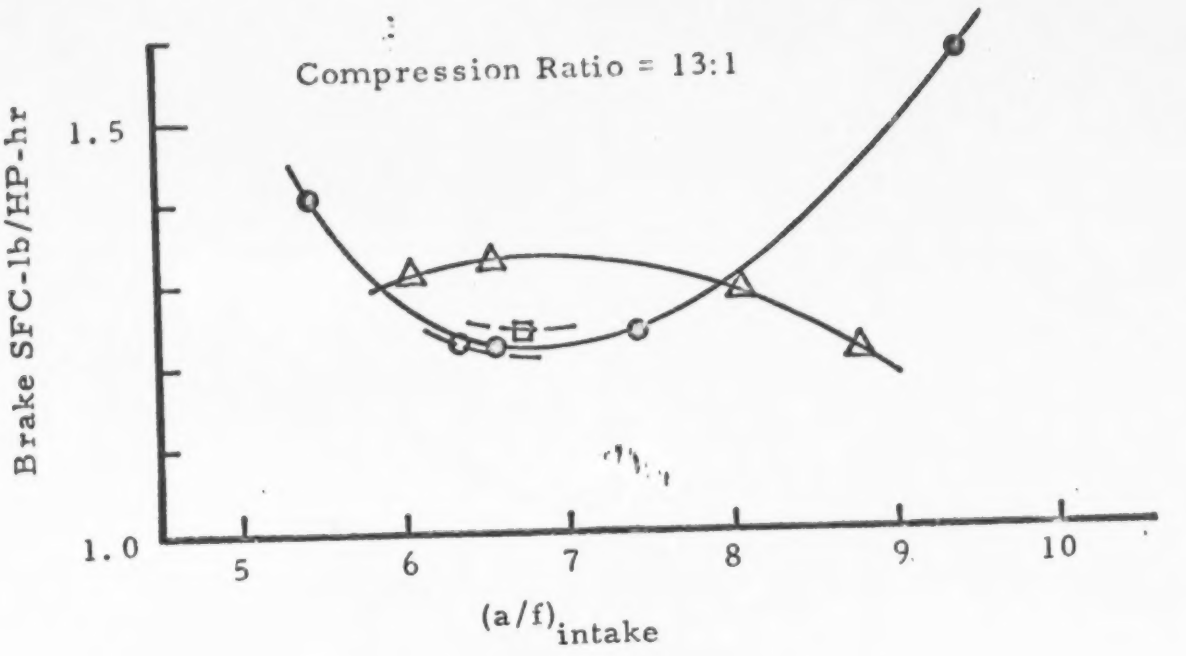
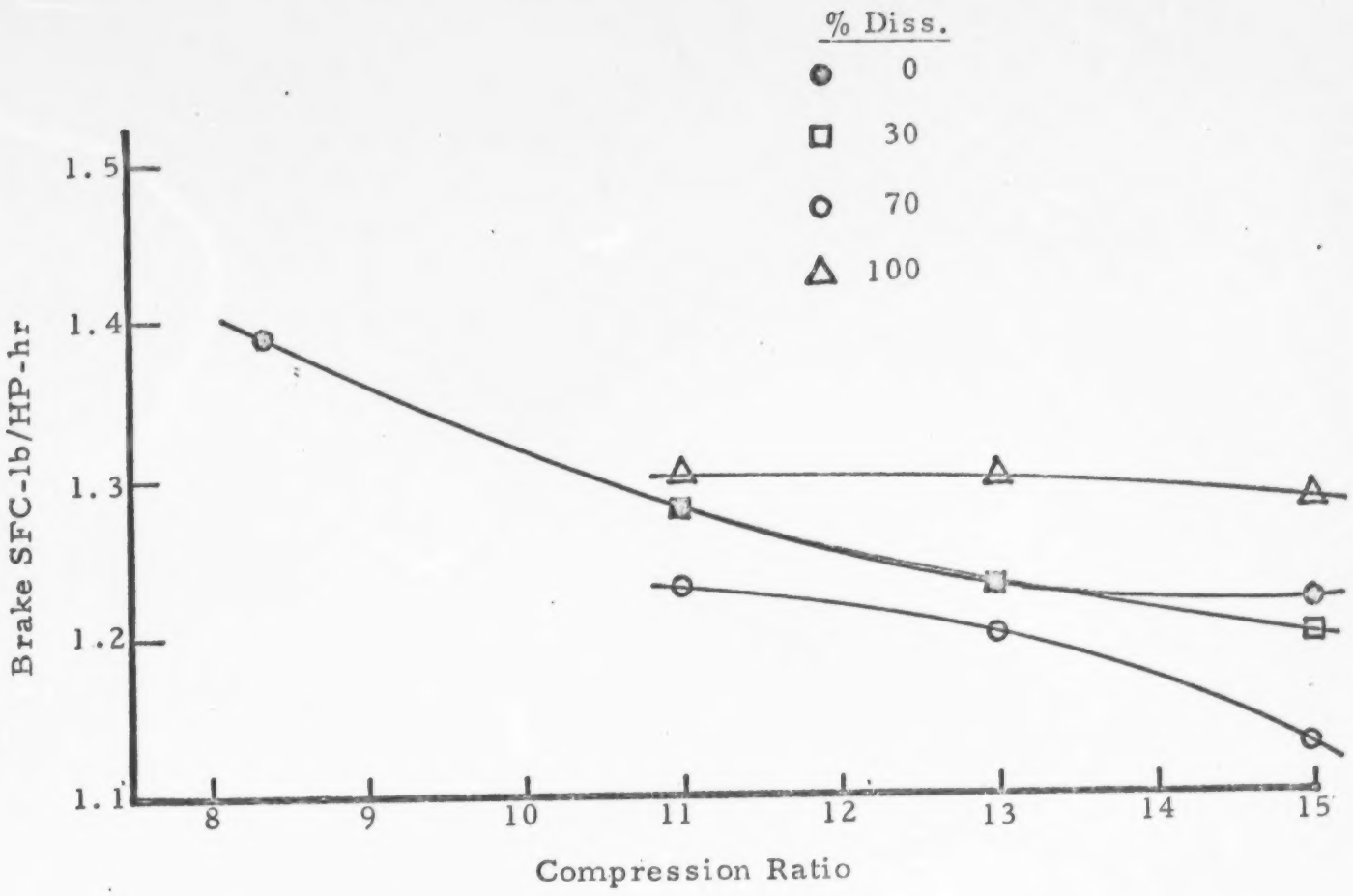


Figure 20. CFR Engine Fuel Consumption, CR = 13:1, 15:1



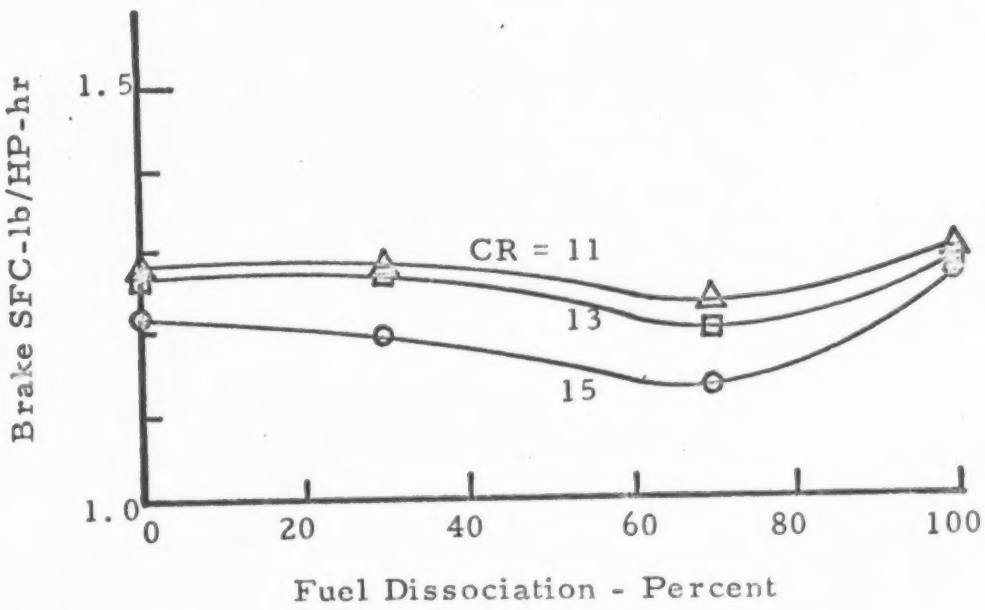
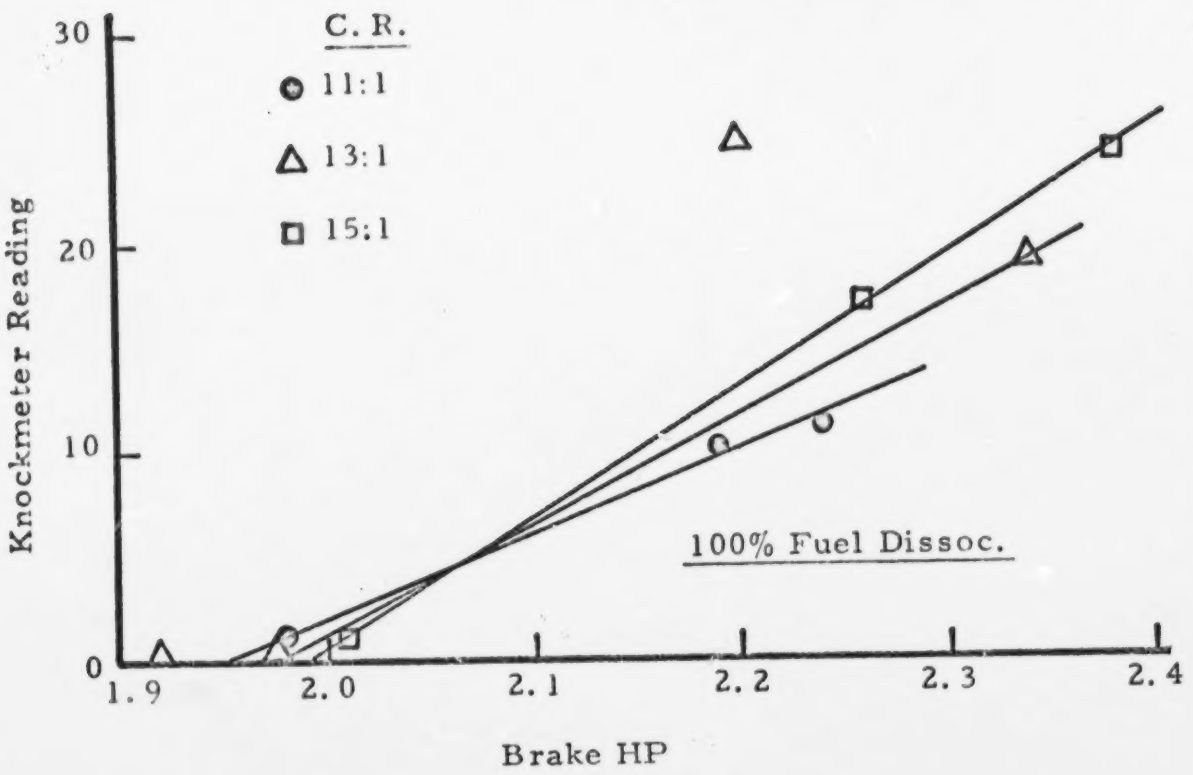


Figure 21. CFR Engine Fuel Consumption



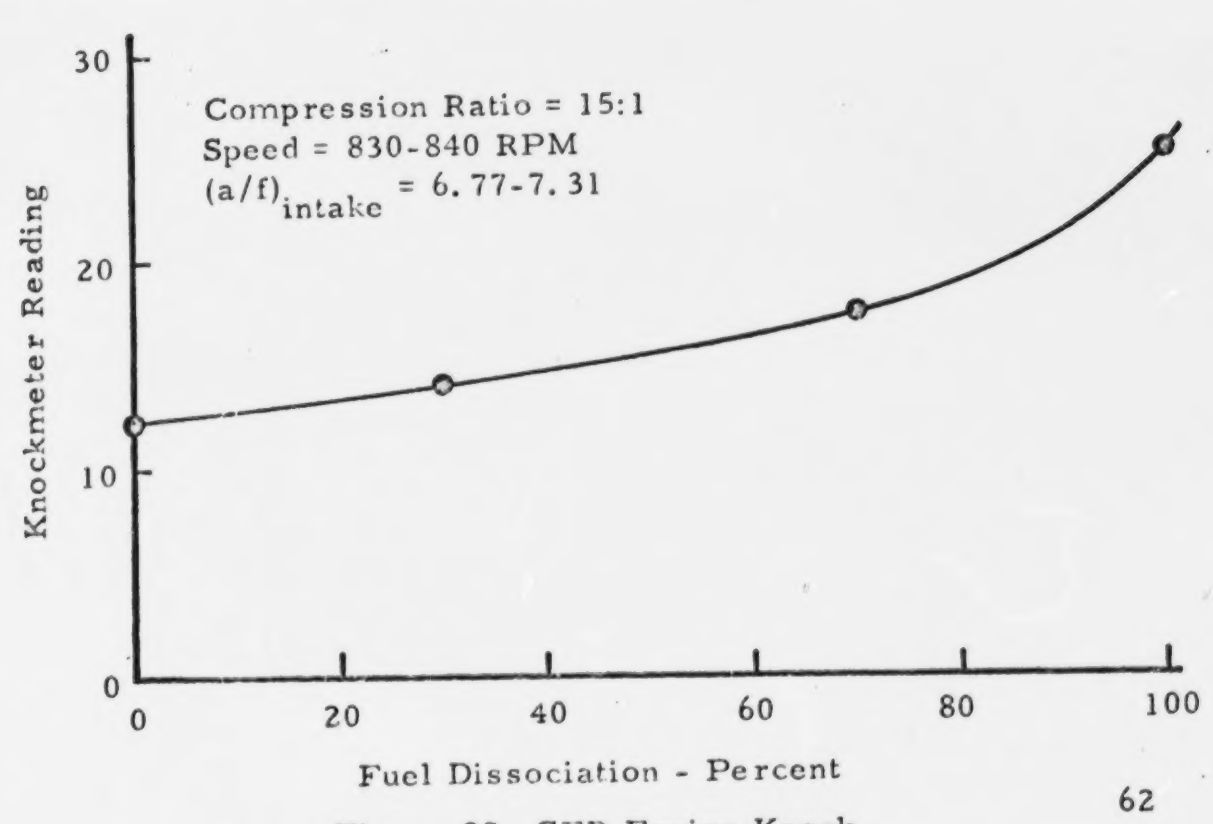


Figure 22. CFR Engine Knock

APPENDIX

Laboratory Engine Test Data

Run	Date	Comp. Ratio	Percent Dissoc.[1]	RPM	Timing[2]	a/f$_i$[3]	a/f$_{ex}$[4]	HP[5]	SFC[6]
1	8/25	8.4	0	860	14.0	6.95	7.25	2.34	1.39
2		8.4	0	850	22.0	8.80	9.25	2.46	1.085
3		8.4	0	859	22.0	5.27	6.11	2.75	1.515
4	8/27	11	0	875	17	6.4	6.76	2.66	1.295
5		11	0	884	17	7.5	7.97	2.43	1.285
6	8/28	11	0	894	22	8.8	9.11	1.97	1.36
7		11	0	894	22	8.8	8.90	1.97	1.36
8		15	0	867	10	5.5	5.9	2.85	1.37
9		15	0	872	14	6.6	6.72	2.94	1.182
10		15	0	862	17	7.55	7.85	2.52	1.21
11		15	0	790	17	9.05	9.65	2.07	1.189
12	8/29	15		884	13	6.07	6.84	3.42	1.70
13		15		870	11	7.1	7.47	2.98	1.89
14		15		840	16			2.78	
15		15		866	16	7.7	8.04	2.86	1.167
16		15		840	23	9.05	9.65	2.43	1.157
17		11	29.8	874	15	5.25	6.0	2.70	1.49
18		11	29.8	874	15	5.25	5.93	2.70	1.49
19	9/8	8.4		880	15			2.45	
20		8.4		885	15	5.5	6.29	2.54	1.595
21		8.4		880	15	6.3	6.56	2.57	1.412
22		8.4		868	15	7.5	7.94	2.26	1.372
23		8.4		845	22	9.15	9.50	1.94	1.340
24	9/10	8.4		856	22	8.9	9.48	1.90	1.400
25		11		892	15	5.27	6.07	2.98	1.770
26		11		876	15	6.4	6.58	2.84	1.271
27		11		880	17	7.55	7.92	2.55	1.220
28		11		870	22	8.9	9.42	2.03	1.321
29		15		880	1	5.45	6.1	3.05	1.786
30	9/11	15		880	14	6.45	6.93	2.84	1.232
31		15		850	17	7.9	8.46	2.37	1.232
32		15		874	17	10.2	10.6	2.02	1.218
33		15		885	15	6.45	6.89	3.15	1.250
34	9/12	15		860	15	7.75	8.50	2.65	1.232
35		15		852	22	9.70	10.4	2.195	1.185
36		8.4	0	862	13	5.43	6.26	2.56	1.615
37		8.4	0	840	13	6.6	7.20	2.38	1.407
38		8.4	0	844	15	7.84	8.62	2.00	1.463
39		11	0	870	15	5.5	6.35	2.83	1.438
40		11	0	868	15	6.65	7.09	2.67	1.270
41		11	0	865	15	7.45	8.21	2.34	1.312
42		13	0	885	15	5.43	6.40	2.87	1.410

See last page for footnotes.

Laboratory Engine Test Data

Run	Knock Reading	T_1[7]	T_2[8]	T_7[9]	T_{ex}[10]	Meth.[11]	Form[12]	CO_2[13]	O_2	CO
1	0	39	78	75	868	not meas.	not meas.	12.7	2.3	0
2	0	37	85	81	772	"	"	10.1	6.5	0
3	0	38	50	79	822	"	"	12.4	.1	2.6
4	0	43	77	79	888	"	"	14.0	1.0	0
5	0	38	70	77	822	"	"	11.8	4.1	0
6	0	42	85	76	758	"	"	10.0	6.2	0
7	0	40	89	76	758	"	"	9.6	7.0	0
8	4	43	75	75	842	"	"	11.8	.2	4.8
9	7	38	66	74	878	"	"	13.3	.7	0
10	2.5	38	68	74	793	"	"	11.2	3.6	0
11	0	40	81	74	720	"	"	9.1	6.9	0
12	18	32	45	76	888	"	"	13.8	1.2	0
13	0	32	44	73	850	"	"	12.3	2.9	0
14	0	32	47	76	794	"	"	11.6	4.0	0
15	7	36	46	75	794	"	"	11.4	4.2	0
16	1	36	74	78	710	"	"	9.5	7.2	0
17	7	36	76	78	842	"	"	11.0	.6	4.5
18	7	36	76	78		"	"	11.7	0	3.5
19	0	50	99	80	878	"	"			
20	2	48	105	83	882	"	"	12.4	.2	1.6
21	2	42	92	92	920	"	"	14.0	.3	0
22	2	42	78	82	850	"	"	11.5	3.9	0
23	0	40	70	81	770	"	"	9.3	6.6	0
24	0	40	80	89	777	"	"	9.6	6.7	0
25	0	42	73	80	844	"	"	11.8	.2	3.2
26	4	42	70	81	892	"	"	14.0	.4	0
27	3	50	69	82	810	"	"	11.8	4.0	0
28	1	39	78	81	752	"	"	9.8	6.7	0
29	25	43	75	82	853	"	"	11.6	.8	2.8
30	0	41	71	75	840	769	83.1	11.2	1.2	0
31	0	46	83	75	750	933	96.5	10.8	4.8	0
32	0	44	71	77	690	1262	112.8	8.4	8.0	0
33	0	35	48	75	845	2960	209.1	13.3	1.7	0
34	0	32	45	70	800	3290	180.5	11.0	5.2	0
35	0	32	47	70	710	2080	119.7	8.4	7.8	0
36	0	45	73	67	882	834	61.0	12.0	.6	2.6
37	0	44	70	83	900	549	71.5	13.0	2.2	0
38	0	32	72	74	840	769	89.4	10.0	5.0	0
39	0	45	73	76	862	1151	69.2	11.6	.6	2.0
40	0	42	71	76	872	769	81.3	12.6	1.8	0
41	0	42	71	76	830	769	84.9	10.9	4.4	0
42	0	44	72	75	833	1151	73.4	11.8	0.8	2.0

Laboratory Engine Test Data (continued)

Run	Date	Comp. Ratio	Percent Dissoc.[1]	RPM	Timing[2]	a/f_i[3]	a/f_{ex}[4]	HP[5]	SFC[6]
43	9/12	13	0	876	15	6.55	6.79	2.76	1.225
44		13	0	852	15	7.45	8.16	2.44	1.242
45	9/15	11	31.	880	15	5.68	6.46	2.72	1.401
46		11	34.2	866	15	6.75	6.97	2.64	1.242
47		11	33.3	820	15	7.5	8.42	2.32	1.268
48		11	34.4	810	15	9.37	10.42	1.89	1.275
49		15	30.7	850	15	5.52	6.46	2.86	1.310
50	9/16	15	34.1	880	15	6.8	7.17	2.52	1.248
51		15	34.8	828	15	7.5	7.74	2.48	1.158
52		15	35.0	800	15	9.5	10.6	2.0	1.170
53		15	69.5	825	10	6.0	6.61	2.69	1.231
54		15	67.7	850	10	6.45	6.71	2.75	1.160
55		15	69.2	840	10	7.28	7.56	2.55	1.133
56		15	66.0	835	10	8.69	9.48	2.23	1.210
57	9/17	11	67.6	800	10	6.1	6.70	2.54	1.261
58		11	68.4	825	10	6.4	6.77	2.54	1.268
59		11	70.1	838	10	7.57	7.92	2.31	1.230
60		11	69.7	822	10	9.35	9.22	1.92	1.235
61		11	100	834	10		12.02	1.50	1.276
62		11	100	819	10		13.73	1.23	
63		11	100	800	10		19.0	.67	
64			100						
65		15	100	820	10		9.81	1.85	1.29
66		15	100	830	10		11.52	1.66	
67		15	100	840	10		12.52	1.44	
68		15	100	805	10		14.38	1.10	
69	9/24	11	100	825	10	7.89	8.2	1.98	1.287
70		11	100	830	10	5.77	6.51	2.24	1.427
71		11	100	827	10	6.48	6.86	2.19	1.339
72		13	100	826	10	6.52	7.01	2.20	1.330
73		13	100	844	10	6.15	6.46	2.34	1.315
74		13	100	842	10	8.8	9.67	1.92	1.214
75		13	100	868	10	8.1	8.73	1.975	1.295
76		15	100	872	10	8.1	8.78	2.01	1.270
77		15	100	807	10	6.5	7.00	2.26	1.278
78		15	100	840	10	5.9	6.52	2.38	1.322
79	9/25	8.4	0	764	10	3.71	5.65	2.38	2.30
80		8.4	0	850	10	4.52	6.24	2.56	1.88
81		13	0	856	10	9.14	10.3	1.66	1.582
82		13	32.9	842	10	6.75	6.84	2.67	1.245
83		13	65.1	836	10	6.36	6.47	2.66	1.229
84		15	100	834	10	6.58	7.75	2.26	1.305
85		15	100	832	10	6.58	7.89	2.26	1.305

Laboratory Engine Test Data (continued)

Run	Knock Reading	T_1 [7]	T_2 [8]	T_7 [9]	T_{ex} [10]	Meth. [11]	Form [12]	CO_2 [13]	O_2	CO
43	0	45	75	77	864	934	86.0	13.4	1.2	0
44	0	42	72	77	810	879	97.8	11.2	4.5	0
45	0	35	70	74	900	493	36.7	13.4	.4	.8
46	0	32	77	74	888	274	44.4	13.6	1.6	0
47	0	34	78	74	810	403	46.0	11.3	5.1	0
48	0	34	81	74	728	622	62.1	8.8	8.1	0
49	0	36	84	74	848	625	35.9	13.3	.8	1.6
50	0	32	98	71	810	293	45.3	13.4	2.2	0
51	0	32	98	69	760	403	57.1	12.2	2.6	0
52	0	31	75	70	708	732	72.4	8.6	8.2	0
53	0	30	80	72	887	234	21.2	13.3	.7	.4
54	34	32	70	74	893	194	30.3	14.2	.8	0
55	17	32	75	72	830	146	24.8	11.8	3.0	0
56	0	31	74	69	760	220	23.7	9.9	6.9	0
57	0	34	55	73	920	194	<16.3	13.5	.9	.3
56	0	35	74	74	915	98	<16.3	14.2	1.0	0
59	0	35	77	73	850	109	12.2	12.1	4.1	0
60	0	36	77	74	770	124	16.3	10.0	6.4	0
61	0	74	102	73	690	7.3	undetect.	7.7	9.9	0
62	0	77	106	73	665	undetect.	"	6.4	9.6	0
63	0	81	107	73	563	"	"	4.3	12.5	0
64										
65	0	77	107	73	750	"	"	8.9	6.9	0
66	0	77	106	73	708	"	"	8.2	8.6	0
67	0	81	107	72	668	"	"	7.4	10.4	0
68	0	77	107	74	622	"	"	6.0	11.0	0
69	1	73	104	71	802	"	"	11.8	4.7	0
70	11	75	107	73	900	"	"	15.0	.5	.6
71	10	78	109	74	888	"	"	15.0	1.4	0
72	25	79	109	73	859	"	"	13.5	1.8	0
73	19	81	110	75	892	"	"	15.0	1.0	0
74	0	80	110	74	750	"	"	10.2	7.6	0
75	0	81	110	74	778	"	"	11.2	5.9	0
76	1	81	110	75	773	"	"	11.4	5.6	0
77	17	81	110	75	846	"	"	14.4	1.8	0
78	24	81	110	75	878	"	"	14.8	0.4	0.3
79	0	46	70	76	758	3350	104	7.8	.45	6.3
80	0	45	69	79	818	2030	75	8.3	.53	5.7
81	0	51	77	80	778	960	83.1	8.6	8.4	0
82	0	42	72	79	860	356	61	13.4	1.4	.8
83	30	36	66	81	893	164.5	24.5	15.6	1.0	0
84	12	64	74	83	854	undetect.	undetect.	14.2	2.9	0
85	11	76	77	84	846	"	"	14.2	3.0	0

Laboratory Engine Test Data

Run	Date	Comp. Ratio	Percent Dissoc.[1]	RPM	Timing[2]	a/f_i[3]	a/f_{ex}[4]	HP[5]	SFC[6]
86	9/29	15	0	840	10	7.3		2.51	1.227
87		15	30	840	10	7.17		2.41	1.288
88		15	70	840	10	6.77		2.42	1.268
89		15	100	830	10	7.31		2.12	1.300
90		15	70	840	10	7.71		2.29	1.234
91		15	70	842	10	7.76		2.33	1.213

Laboratory Engine Test Data

Run	Knock Reading	T_1[7]	T_2[8]	T_7[9]	T_{ex}[10]	Meth.[11]	Form[12]	CO_2[13]	O_2	CO
86	22	49	70	80	837	undetect.	undetect.	not measured		
87	28	45	70	81	816	"	"		"	
88	35	42	71	81	833	"	"		"	
89	52.5	82	109	80	820	"	"		"	
90		43	85	80	803	"	"		"	
91	30				803	"	"		"	

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1. (Gaseous Fuel Flow Rate x 100)/(Gaseous + Liquid Fuel Flow Rate)
2. Degrees Before Top Dead Center
3. Measured Intake Air Flow Rate/Measured Total Fuel Flow Rate
4. 4.31 $(1.5\%CO_2 + \%O_2 + \%CO)/(\%CO_2 + \%CO)$
5. Brake HP: Torque (ft-lb) x RPM x $2\pi/33000$
6. Brake SFC: Total Fuel Flow Rate/Brake HP
7. Temperature (°F) downstream of carburetor, before manifold heater.
8. Temperature (°F) at engine intake port downstream of manifold and heater.
9. Ambient temperature (°F) at Air Flow Meter.
10. Temperature (°F) near engine exhaust port.
11. Methanol concentration in exhaust gas, PPM by volume.
12. Formaldehyde concentration in exhaust gas, PPM by volume.
13. Carbon Dioxide concentration in exhaust gas, percent by volume (typical).

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15. Supplementary Notes			

16. Abstracts A study was conducted to investigate the feasibility of using methanol as a substitute fuel for gasoline to reduce exhaust pollutants emitted from automotive engines. Work was performed in two phases encompassing both automotive and single cylinder laboratory engine tests.

It is concluded that methanol displays significant potential as a pollution control substitute fuel for gasoline. In the automotive tests conducted with a slightly modified, non-optimized engine system, methanol was shown to be a satisfactory fuel from the standpoint of engine operation and to produce methanol emissions as low as 1900 PPM (317 PPM-hexane equivalent). Vehicle mileage was low (7 to 9 mpg) as expected. Suspected high aldehyde emissions were confirmed. It is, however, believed that optimization of the fuel-air ratio, the mixture distribution to the cylinders, and heating of the fuel or fuel-air mixture, will result in improved performance and substantially reduced emissions of all pollutants, except NOx.

(See attached sheet)

17. Key Words and Document Analysis. (a). Descriptors

Methanol
Fuel
Pollutants

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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Continuation of Item 16, Abstracts.

Laboratory engine operation with blends of reform gases ($CO + 2H_2$) and methanol was shown to be successful in improving engine performance (subject to engine knock limitations) and providing major reductions in methanol and formaldehyde emissions. If the reforming technique can be economically implemented in an automotive system, it is highly probable that emission levels can be achieved which are well below those possible with gasoline.